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Population specifications of the European corn borer, Pyrausta nubilalis (Hbn), in field corn

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POPULATION SPECIFICATIONS OF THE EUROPEAN CORN BORER, *PYRAUSTA NUBILALIS* (HBN.), IN FIELD CORN

by

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INTRODUCTION

Introduction of the European Corn Borer into the United States

The European corn borer, Pyrausta nubilalis (Hbn.), was first discovered in the United States in the vicinity of Boston, Massachusetts, in 1917, probably brought over from Europe in shipments of broom corn in the interval from 1909 to 1914. By 1924 there were three main areas of infestation, one in Eastern New England, a second in Eastern New York, and a third in the Lake Erie area. By 1926 the areas of infestation had spread eastward from Lake Erie and westward from the Eastern New York area and coalesced. From that time on the spread was much slower but nevertheless relentless until at the present time it is found in all major corn growing areas of the United States and Canada.

Extensive investigations into the bionomics of this insect have been carried out by Barber (6), Caffrey and Worthley (14), Huber, Neiswander, and Salter (22), and Arbuthnot (3) in the United States and by Stirrett (31) in Canada. The larval habits, larval establishment, moth flight and ovipositional habits have been investigated with reference to ecological and meteorological factors affecting them.

The Biology of the European Corn Borer

The life cycle of the European corn borer consists of the egg stage, usually five larval instars, a pupal stage, and the adult moth.

<u>The egg stage</u>

The eggs are laid in masses of from 1 to 162 individual ova with an average of 15 to 20 eggs, according to Caffrey and Worthley (14). Stirrett (31) gives a value of 15.8 for Chatham, Ontario. The individual egg is thin, scale-like, with a somewhat convex upper surface and a flat under surface. On the average they are 0.97 mm in length and 0.74 mm in width. At the time of oviposition the eggs are greenish white, changing to yellowish two days before hatching. Following this shortly they attain the blackhead stage, so-called because the black larval head capsule is visible through the transparent chorion. The incubation period usually lasts from 4 to 5 days.

The eggs are usually laid on the underside of the leaves of the corn plant, although they have been found on almost all of the aerial portions of the plant. Stirrett (31) states that 94.44% of all egg masses in his study plots were laid on the underside of the leaves, 5.01% on the upper surface, and 0.55% on the stalk.

Egg mortality may be due to low fertility, to the action of predators and parasites, and to mechanical dislodgement from the corn plant. The following mortalities, in percentages, for the above egg population depressants are: non-fertile, 3.8%, Stirrett (31); destroyed by predators, 2.8%, Huber *et al*. (22); dislodged, 11.2%, Huber *et al*. (22), and 1 to 34%, Stirrett (31).

The larval stages

The full-grown larva has an average length of from 20 to 23 mm. The body is dirty white, shading from a light, or dark brown, to pink on the dorsum. The five instars are best differentiated by the width of the prothoracic shield which grows in discrete steps at each molt. The average measurements of the prothoracic shield as given by Caffrey and Worthley (14) are: First instar 0.25 mm, second instar 0.41 mm, third instar 0.71 mm, fourth instar 0.98 mm, and the fifth instar 1.72 mm.

Soon after hatching, the first instar larvae tend to wander from the point of attachment of the egg-mass. Only those larvae which reach the protection of the whorl have a good chance of surviving. Larvae which move toward the margins or tips of the leaves may drop and hang by means of a silken thread spun from the modified salivary glands. It is at this time that dissemination of the corn borer larvae by wind currents is possible.

The second and third instar larvae are principally external feeders although found mainly in the protected environment of the leaf whorl. Some thirds will be found tunneling within the leaf mid-rib.

At about the fourth instar the larvae tend to become borers but by then larval mortality has been heavy. Huber et al. (22) give a mortality of 68.6% up to this stage. Huber et al. (22) give a total larval mortality for the entire larval period of 91.9% for the year 1928. Stirrett (31), at Chatham, Ontario, gives a corresponding average total larval mortality, for a period of ten years, of 72.1%.

The pupal stage

The average length of the pupa has been given by Caffrey and Worthley (14) as 13 to 17 mm. In color they are yellowish-brown with brown to black extremities, the intensity of the coloration increasing with the age of the pupae. This stage is usually found in the larval tunnel or occasionally on the underside of the leaves.

The adult

The adult is a moth of a general yellowish coloration, the male is smaller than the female, and with a reddish brown to grayish fuscous cephalic wing. The female wing span is 25 to 34 mm and the male wing span is 20 to 25 mm. Stirrett (31) states that the moths fly from one half hour before, to 3½ hours after, sunset.

Life cycle at Ames, Iowa

The length of the life cycle is variable depending on climatic conditions prevailing. At Ames, Iowa, the over-wintering larvae which transform to adults emerge as moths toward the last week in May to the first week in June. The larvae work in the corn until the second or third week in July at which time pupation takes place. Toward the last week in July to the first week in August the moths lay the eggs which give rise to the second generation. The second generation larvae reach the fifth instar by fall, in which form they hibernate. The fifth instar larvae surviving the winter pupate in the spring and the emerging moths give rise to the following year's first generation. Although the European corn borer here in Iowa is predominantly bi-voltine the number of generations is variable depending on climatic conditions. One to seven generations are known elsewhere.

Formulation of the Problem

Population specifications

The economic entomologist has come to realize that statistical procedures are powerful research tools and the use of statistically designed experiments has increased considerably in the past two decades. A common statistical tool in use is the analysis of variance, but this technique, although not excessively sensitive to deviations of data from normality, is nevertheless based on normal theory. In order to examine the departure of larval populations of the European corn borer from normality it has been deemed advisable to determine the mathematical model which best describes the distribution of this insect.

In using the term normal, or normality, a specific mathematical model with the formula

$$y = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}} , \quad -\infty < x < \infty ,$$

is to be understood, which depends on two parameters, the population mean μ and the population variance σ^2, which are not functionally related.

Transformations

For non-normal data various transformations have been suggested, Bartlett (7), which will make the sample variance independent of the sample mean and may even normalize the data. Beall (11) developed a transformation applicable to data in which the variance and the mean are functionally related

$$\mu_2 = \mu_1' + \lambda\mu_1'^2 .$$

It is intended, in this thesis, to examine the transformation applicable to data on the European corn borer, its effectiveness in making the sample variance independent of the sample mean, and the possible approach to normality of the transformed data.

Efficiency of size and shape of plot

In the early decades after the introduction of the European corn borer into this country the emphasis was placed primarily on investigations of the bionomics of this insect. With the advent of the new organic insecticides and their increased residual effects the control of this pest by the use of sprays has become economically feasible and greater emphasis has therefore been placed on chemical control. As a guide in designing experiments with the European corn borer for the study of chemical treatments, the efficiency of the size and shape of plots will be examined.

Sampling from contagious larval populations

It is intended, in this thesis, to examine the sampling of contagiously distributed insect populations for possible application to plot work.

PROCEDURES

Uniformity Data

Uniformity data may be defined as data taken from a population which has not been subjected to treatments and is collected from small plots over a continuous area. Uniformity data are used to study the variability due to the size and shape of plot as a guide in designing experiments to be analyzed by means of the analysis of variance or for sampling investigations.

The best known uniformity data study is that of H. Fairfield Smith (30) in which he harvested a crop in very small plots and compared the efficiency of varying sizes of plots. Beall (9) used uniformity data in studying sampling techniques with the Colorado potato beetle, *Leptinotarsa decemlineata* (Say.). Bancroft *et al.* (5) have also used uniformity data in studying plot size in experiments with peanuts.

For the present study the uniformity data consist of European corn borer counts made in four experimental areas each of approximately one-third of an acre. One area was totally dissected and three areas were sampled by dissecting one plant from each hill.

Procuring the Data

Descriptions of the experimental areas

In 1952 the levels of infestation were generally low in Southern and Central Iowa but medium to high in the northwestern corner of the state. A heavily infested cornfield from which to select an experimental area was finally located in Lyon County. In contrast to 1952 the infestations in Central Iowa during 1953 were relatively high while adverse meteorological factors reduced the first generation infestations in the northwestern corner of Iowa to a very low level. Three suitable cornfields were located in Boone County in the vicinity of Madrid, Iowa.

An experimental area in Lyon County, Iowa, 1952. The cornfield from which experimental area number one was selected was located on the farm of Floyd Hohman, one mile west of Larchwood, Iowa. The 40 acre cornfield was planted at the foot of a very gentle slope so that approximately one-half of the cornfield was on level ground. The field had been planted to Pioneer 349 at an average rate of two seeds per hill.

The experimental area was selected on level ground, eighteen hilss from, and in the center of the northern boundary of the cornfield. The rows, running north and south were planted 3.5 feet apart with the hills spaced at 2.3 feet within the rows.

The experimental area was square, 126 feet to a side, and consisted of thirty-six rows, each row with fifty-four hills. The 1944 hills were divided, for convenience, into 324 plots, each plot consisting of two parallel, three-hill row-segments.

The plants within the experimental area were identified by a tag on which a coordinate and plant number were recorded. The coordinate system had its origin at the northeastern corner of the field. The plant numbering was consecutive from 1 to 3205 and started at hill 1-1, where 1-1 is of the form (x,y) where x refers to the row and y to the hill, x = 1,2,....,36 and y = 1,2,....,54.

The experimental area was dissected in 4.5 days, from July 29 to August 2. On the morning of the first day the eight boys hired to do the dissections were taught how to dissect the corn plants, to identify the various larval instars, and how to record data.

The plots dissected each day were selected at random. The complete plot was cut down as a unit and the plants taken out of the field to the dissectors who then took their plants for dissection from a common pile. The tags from each day's dissections, on which the data were recorded, were later identified as to day of dissection. The data gathered consisted of number of cavities, pupae, and all larval instars per plant dissected.

Three experimental areas in Boone County, Iowa, 1953. The three experimental areas dissected in 1953 were similar in the following respects: All three were located in the vicinity of Madrid, Boone County, Iowa; they were similar in size, approximately one-third of an acre; all three fields had been either cross-checked or power-checked at 3.5 feet so that each area was symmetrical with thirty-six rows and thirty-six hills per row for a total of 1296 hills. One plant was selected at random and dissected out of each hill. The number of plots was the same as in the previous year's area, 324, but due to the different hill spacing each plot contained only four hills, two parallel row-segments of two hills each. The method of identification was similar to that used for area No. 1 except that only the coordinate number was used since only one plant per hill was generally taken. The plant to be dissected in each hill was selected at random by the simple procedure of tossing a coin. If there were more than two plants in the hill the plants present were divided into two groups as often as necessary to make the final choice one between two individual plants. Whenever a missing hill was encountered one of the hills remaining in the plot was chosen at random and another plant selected at random from those not previously tagged. The data gathered again consisted of number of cavities, pupae, and all larval instars per plant dissected, plus the number of plants in each hill. The three areas have been numbered 2, 3 and 4.

Experimental area number two was selected from a twenty-two acre field of corn on the farm of Carl Rose, four miles west of Madrid, Iowa, on the western side of the Des Moines River. The cornfield had been planted to two different gybrids; the eastern twenty-one rows were planted to Funk's G 54 and the rest to DeKalb 347. Two planting rates had been used, three seeds per hill with the Funk and four seeds per hill with the DeKalb hybrid. The experimental area was located on the eastern edge of the cornfield ten hills in from the northern margin. The origin for the coordinate system was located at the northeastern corner of the experimental area.

The experimental area was dissected in 2.5 working days but in 4.5 days elapsed time since no dissections were made on Saturday or Sunday, July 18 and 19. Dissections were started on the afternoon of July 16; however, the afternoon was used primarily to train the dissectors.

The plots on this experimental area were again selected at random, all four plants in each plot were cut down at the same time and taken out of the field for dissection. The data from plots dissected each day were recorded to allow a study of larval development from day to day. The level of infestation was graded visually on 600 plants. A code developed at the Ankeny Corn Borer Laboratory, see Appendix A, was used.

Experimental area number three was selected from a thirty-six acre cornfield on the farm of W. B. Hurley, l-cated one mile west of Madrid, Iowa. The cornfield was planted to Funk's G 91 at the rate of three seeds per hill. The experimental area was located on almost level ground, 158 hills from the southern, and twenty-nine hills from the western margin of the field.

The area was dissected in two days; one-half the area was finished each day. The plots in this area were not selected at random. The selection of the plots to be dissected the first day was arbitrary and consisted of a checkerboard pattern, that is, all odd plots in odd plot-columns and all even plots in even plot-columns were dissected the first day. This procedure was deemed permissible because the rate of development of the borer population was expected to be small at this time.

Experimental area number four was selected from a sixty acre cornfield on the farm of Jack Brown located about one mile south of Madrid, Iowa. The cornfield was planted to Pioneer 301B at the rate of three seeds per hill. The experimental area was located five-hundredths of a mile south of the farmhouse and thirty rows from the western margin of the field.

The area was dissected in 1.25 days. An attempt was made to dissect it in one day but due to unforeseen circumstances seven rows were left for the next day. The plants in this area were dissected *in situ* since there was no easily accessible open place where the dissectors could sit.

Processing the Data

The tags brought in from the field were arranged in order by plots and tabulated. The data were punched on IBM cards from these tables. Summary cards were prepared from the cards representing individual plants to give all other necessary totals. In the case of area number one, the summary cards were made for hills, row segments and for plots. For areas two through four, only plot summary cards were made. From the IBM cards, all frequency distributions, tabulations and sums of squares were made for the analysis of the data. The method is quite flexible and allows the efficient handling of large masses of data. The data consisted of information on cavities, pupae, fifth, fourth, third and second instar larvae: by plants, by hills, by rows, and by plots for area number one; and by plants and by plots for areas number two, three and four. Some additional information on time of dissection and visual evaluation of infestation based on two systems of rating is also included.

The data, by plots, are included in appendix C.

Information on visual evaluation of infestation is not included since it is on a plant basis and the number of plants per plot is not constant.

ANALYSIS

Population Specifications

Contagious distributions

Contagion may be defined as an inflation of the variance in a population which should be adequately described by the Poisson Law. According to Feller (19) there are two types of contagion, "true" contagion and "apparent" contagion. "True" contagion results when the occurrence or non-occurrence of an event changes the probability of the event again occurring or not. The best example of this mechanism will be the case of an epidemic of measles. If a member (x) of a household contracts the disease the probability of the other members contracting the disease is greatly increased. On the other hand, the fact that x has had measles greatly decreases the probability of his contracting the disease again. "Apparent" contagion is the result of heterogeneity in the parent population variance. In this case we may visualize a Poisson distribution with a different value of the parameter λ, the mean, at different places in the field. It is logical to assume that λ will have some particular distribution over the field which leads to the specific contagious distributions that have been proposed. The contagious distributions presented below fall into two groups: one group, exemplified by the negative binomial, in which the Poisson parameter is distributed as a Gamma variate, and another larger group in which the Poisson parameter is distributed according to the Poisson Law.

The mathematical development of the contagious distributions has been due to several fields of endeavor. The negative binomial distribution was proposed by workers investigating the multiple occurrence of accidents. The Polya-Eggenberger distributions are a direct result of an analytical investigation of contagion. The study of the number of plants per quadrat led to the Thomas distribution while the study of insect larval distributions is responsible for the Neyman and the Poisson binomial distributions.

Five contagious distributions were found in the literature. A short discussion of each is given below. For a fuller discussion and mathematical presentation see appendix B.

The negative binomial distribution. The negative binomial distribution has probably received more attention from statisticians than any of the other existing contagious distributions. It was first proposed by Greenwood and Yule (21) who were investigating the distribution of accidents. It was later independently derived by Polya (26) in an analytical investigation of contagious probabilities. Fisher (20) investigated the efficiency of fitting by the method of moments and derived an expression for calculating this efficiency. Anscombe (2) has extended Fisher's work and plotted the efficiencies. Bliss (13) discussed at length the fitting of the negative binomial and appended a paper by Fisher on the method of maximum likelihood. Evans (18) applied the negative binomial to plant and insect data, and has a very thorough mathematical development of the distribution.

The Neyman contagious distributions. The Neyman distributions consist of an infinite family of distributions of increasing complexity. Neyman (25) developed the first three which he designated Type A, B, and C. The assumed model was one of entomological interest and was probably based on larvae of the European corn borer. Beall, 1952, in a lecture before the Biostatistic conference at Ames, Iowa, and more recently in Biometrics (12), has extended and generalized the Neyman distributions. Shenton (28) investigated the efficiency of the method of moments for the type A distribution. Bateman (8) has recently discussed the power of the index of dispersion for the type A. The more complex distributions have not been investigated.

The Thomas distribution. Another contagious distribution recently developed for describing the distribution of plants, Thomas (33), is of importance in plant ecology.

English writers refer to this distribution as the double Poisson distribution. It has not been extensively investigated.

The Polya-Eggenberger distributions. Two distributions were fitted by Beall (10) to European corn borer larval populations under the above name. The distribution called type one by Beall is identical with the negative binomial. The other, called type two by Beall, which has been designated as the Polya-Aeppli distribution by English writers, is distinct. Evans (18) discussed the fitting of this distribution.

The Poisson binomial distribution. Skellam (29) has given the probability generating function of this distribution and successfully fitted some data on a sedge, *Carax flacca* Schreib., as given by Archibald (4). This distribution was independently derived by the author for describing the distribution of larvae of the European corn borer. A method of fitting is described in appendix B.

Fitting the distributions

Of the contagious distributions found in the literature only three were deemed appropriate in the case of populations of corn borer larvae. These three distributions are: (1) the negative binomial which assumes that the variable Poisson parameter is distributed as a Gamma variate; (2) the Neyman type A which assumes Poisson survival from each egg mass where the egg masses are distributed as Poisson variates; and (3) the Poisson binomial which assumes binomial survival from each egg mass where the egg masses are again distributed as Poisson variates.

Fitting the negative binomial. The negative binomial is the easiest distribution to fit. The fitting is best illustrated by fitting the frequency distribution for total borers per plot from field number 4. (See Table 9.)

The moments of the frequency distribution were calculated by first calculating the factorial moments as follows:

x	f_x	S_2	S_3
0	188		
1	83	136	
2	36	53	74
3	14	17	21
4	2	3	4
5	1	1	1
	324	210	100

Hence,

$$\mu'_{[1]} = S_2/324 = 210/324 = 0.648148 = \bar{x}$$
$$\mu'_{[2]} = S_3\, 2!/324 = (2)(100)/324 = 0.617282$$
$$\mu'_2 = \mu'_{[1]} + \mu'_{[2]} = 1.265430$$
$$\mu_2 = \mu'_2 - (\mu'_1)^2 = 0.845334 = \hat{\sigma}^2 .$$

Having the estimates of the first two moments, equations (10), appendix B, are used to get the moment estimates of the parameters as follows:

$$\hat{k}_m = \bar{x}^2/(\hat{\sigma}^2 - \bar{x}) = (0.648148)/(0.197186) = 2.130454$$
$$\hat{p}_m = (\hat{\sigma}^2 - \bar{x})/\bar{x} = \bar{x}/\hat{k}_m = (0.648148)/(2.130454)$$
$$= 0.304229 .$$

Using the moment estimates of k and p the maximum likelihood estimates using equation (12), appendix B, are calculated.

Substituting $\hat{k}_m$ in equation (12), appendix B, the value of $z_1 = -0.436146$. A negative value of z indicates that the moment estimate of k is too large. Since a value of k is required which will make z vanish, an arbitrary value of $k < \hat{k}_m$ is chosen which will make z_2 positive and interpolation is used, for $z = 0$, between the values of k. Letting $k_2 = 1.8$ and again substituting in equation (12) the value of $z_2 = 0.112587$. Interpolating between the two k's for $z = 0$ the maximum likelihood estimates of k and p are:

$$\hat{k}_{ml} = 1.858566 \quad \text{and} \quad \hat{p}_{ml} = 0.348735 .$$

Using logarithms the probability of zero is next calculated as follows:

$$P_o = 1/(1 + p)^{\hat{k}_{ml}}$$

$$\log P_o = \log 1 - k_{ml} \log (1 + \hat{p})$$

$$= 0 - (1.858566)(\log 1.348735)$$

$$= \bar{1}.758522$$

$$P_o = \text{antilog } \bar{1}.758522$$

$$= 0.573414 \; ,$$

hence

$$P_1 = P_o \hat{k}\hat{p}/1(1+\hat{p}) = \frac{(0.573414)(1.858566)(0.348735)}{1(1.348735)}$$

$$= 0.275559$$

$$P_x = P_{x-1} \; (\hat{k}+x-1)\hat{p}/x(1+\hat{p}) \quad .$$

Once the probabilities are calculated they are multiplied by the total number of plots in the frequency distribution to get the expected numbers, which completes the fitting.

Fitting the Neyman type A distribution. The Neyman type A requires more computation than does the negative binomial. The moment estimates of the parameters m_1 and m_2 are identical with those for k and p in the negative binomial. Since the frequency of zero is quite large it was decided to fit the curve using the frequency of zeros.

Employing the moment estimate of m_2 the following relationship, due to Evans (18), may be used to calculate the zero frequency estimate of m_2:

$$(\hat{m}_2)_{i+1} = c - ce^{-(\hat{m}_2)_i} , \qquad \text{where } c = \bar{x}/\ln(N/n_0) .$$

The relationship converges rather slowly, but by using Tables of the descending exponential, U. S. Bureau of Standards (34), the thirty trials required to estimate m_2 in this case were performed in a very short time.

The value of m_2 was estimated to be 0.359842 instead of 0.304229 which was the value obtained by the method of moments. The values for $\hat{m}_1$ and $\hat{m}_2$ are now

$$\hat{m}_1 = 1.801201 \quad \text{and} \quad \hat{m}_2 = 0.359842 .$$

The next step is the calculation of e^{-m_2} which is computed from the Tables of the descending exponential by looking up two values of e^{-x} as follows:

$$e^{-0.359842} = e^{-0.3598-0.000042} = e^{-0.3598}\, e^{-0.000042}$$

Both values on the right being available in the tables, then

$$e^{-\hat{m}_2} = 0.697787 .$$

Two different sets of multipliers have to be calculated in order to compute the required probabilities.

First the terms in the expansion of $e^{\hat{m}_2}$ are required, i.e.

$$e^{\hat{m}_2} = 1 + \hat{m}_2 + \hat{m}_2^2/2! + \hat{m}_2^3/3! + \hat{m}_2^4/4! + \hat{m}_2^5/5! + \cdots\cdots .$$

In the present case only the first five terms in the above expansion are needed. These were obtained by computing $\hat{m}_2$ to ten decimals and performing the indicated operations directly. If a large number of terms are to be used it is preferable to employ logarithms.

The second set of multipliers required is $\bar{x}e^{-\hat{m}_2}/i$, where i will go from 1 to n, and in this instance only five terms are needed so that n = 5. These terms are easily computed by multiplying $\bar{x}e^{-\hat{m}_2}$ by the reciprocal of 1, 2, 3, 4, and 5.

In the present case the terms in the expansion of $e^{\hat{m}_2}$ were

$$\hat{m}_2^0 = 1 \div 0! = 1.000000$$
$$\hat{m}_2^1 = 0.359842 \div 1! = 0.359842$$
$$\hat{m}_2^2 = 0.129486 \div 2! = 0.064743$$
$$\hat{m}_2^3 = 0.046594 \div 3! = 0.007765$$
$$\hat{m}_2^4 = 0.016766 \div 4! = 0.000698$$

and

$$\bar{x}e^{-\hat{m}_2}(1) = 0.452269$$
$$\bar{x}e^{-\hat{m}_2}(0.5) = 0.226135$$
$$\bar{x}e^{-\hat{m}_2}(0.333333) = 0.150756$$
$$\bar{x}e^{-\hat{m}_2}(0.25) = 0.113067$$
$$\bar{x}e^{-\hat{m}_2}(0.2) = 0.090454\ .$$

The probability of zero is next calculated as follows:

$$P_0 = e^{-\hat{m}_1(1-e^{-\hat{m}_2})} = e^{-0.544346} = 0.580221$$

$$P_1 = \bar{x}e^{-\hat{m}_2}(\hat{m}_2^0/0!)P_0 = (0.452269)(1)(0.580221)$$

$$= 0.262416$$

$$P_2 = \frac{\bar{x}e^{-\hat{m}_2}}{2}\left(\frac{m_2^0}{0!}P_1 + \frac{m_2}{1!}P_0\right)$$

$$= (0.226135)\left[1(0.262416) + (0.359842)(0.580221)\right]$$

$$= 0.106556\ ,$$

etc.

By using two sheets of ruled paper, one on which to record the probabilities as they are calculated, and one on which to record the multipliers, the calculation of the above probabilities is greatly simplified. The terms in the expansion of $e^{\hat{m}_2}$ are placed at the lower left hand corner of the multiplier sheet next to the edge, with the one at the bottom and the lowest value at the top. In line with the one and to the right of it the value of $\bar{x}e^{-\hat{m}_2}$ is entered and all successive values entered over it in descending order, the lowest value required, at the top. By placing the multiplier sheet over the sheet on which the value of P_0 is recorded so that the one is opposite P_0, the required multipliers for the calculation of P_1 are immediately available. Having calculated P_1 it is recorded below P_0 and the multiplier sheet is moved down so that the one is opposite P_1. Using cumulative multiplication P_1 is multiplied by 1 to which is added the product of P_0 and $\hat{m}_2$. This sum is transferred to the keyboard and multiplied by the value of

$\bar{x}e^{-\hat{m}_2}/2$ which is opposite the value of $\hat{m}_2$. P_2 is then recorded below P_1 and the process continued until all the required probabilities have been calculated.

Fitting the Poisson binomial distribution with n = 2. This distribution is intermediate to the preceding two in ease of fitting. Since the moment estimates of m_1 and m_2 for the Neyman type A are already available those values are used to compute the parameters of this distribution as follows:

$$\hat{a} = (n-1)\,\hat{m}_1/n = 2.130454/2 = 1.065227$$
$$\hat{p} = \hat{m}_2/(n-1) = \hat{m}_2 = 0.304229$$
$$q = (1-\hat{p}) = 0.695771$$
$$q^n = q^2 = 0.484097 .$$

Since n = 2, only two multipliers will be required. These are:

$$q^{n-1} = 0.695771$$
$$(n-1)\hat{p}q^{n-2} = (1)\hat{p}(1) = 0.304229 .$$

Using the above values for the parameters and multipliers the required F_x values are next calculated to be:

$$F_0 = e^{-a(1-q^n)} = e^{-0.549554} = 0.577207$$
$$F_1 = \bar{x}q^{n-1}F_0 = (0.648148)(0.695771)(0.577207)$$
$$= 0.260299$$

$$F_2 = \bar{x}\left[(n-1)\hat{p}q^{n-2}F_0 + q^{n-1}F_1\right]$$
$$= (0.648148)\ \left[(0.304229)(0.577207) + (0.695771)(0.260299)\right]$$
$$= 0.231202$$
$$F_3 = \bar{x}\left[(2)(n-1)\hat{p}q^{n-2}F_1 + q^{n-1}F_2\right]$$
$$= 0.206918\ ,$$

etc. Hence the required probabilities are:

$$P_0 = F_0 = 0.577207$$
$$P_1 = F_1 = 0.260299$$
$$P_2 = F_2/2 = 0.115601$$
$$P_3 = F_3/6 = 0.034486\ ,$$

and so on.

In computing the value of chi-square either form of equation (21) appendix B may be used. The right hand form is preferred as involving less work unless the individual chi-squares are to be compared.

Results

In this investigation four experimental areas have been studied. Area number one was completely dissected while areas two, three, and four were sampled.

For the one field which was completely dissected three frequency distributions were fitted. The three frequency distributions were: (1) the distribution of total borers per plant, (2) the distribution of pupae and fifth instar larvae per plant, and (3) the distribution of total borers per plot. Distribution number one, see Table 1, was not fitted by any of the three contagious distributions tried. The smallest value of chi-square was given by the Poisson binomial distribution. From Figure 1 it is evident that there seems to be a tendency for a piling up of frequency at the even numbers of borers, which suggests a counting bias by the dissectors. Since the greatest error would be made with the more immature larval stages, the second frequency distribution listed above was fitted. In this case, see Table 2, the Poisson binomial gave the best fit, the Neyman type A was next, while the negative binomial gave a poor fit. On the plot basis the negative binomial and the Neyman type A distributions both gave excellent fits with the type A being slightly better, see Table and Figure 3.

The three sampled areas were alike in one respect. For high values of the mean the negative binomial gave the best fit while for low values the Poisson binomial was better. Sic frequency distributions were fitted, one on plants and one on plots for each of the three areas. Both frequency distributions for area number two were fitted best by the negative binomial, see Tables and Figures 4 and 5. The Poisson binomial was not fitted since its skewness is less than that of the type A and the fit would not have

Table 1.

Experimental area number 1, total borers per plant

Observed and theoretical frequencies; the values of chi-square and their attached probabilities

Observed			Theoretical		
x	f_x	Poisson	NB*	NTA*	PB(n=2)*
0	355	238.0	324.30	331.79	341.84
1	600	618.9	660.37	654.44	644.37
2	781	804.5	734.06	734.77	728.03
3	567	697.3	610.45	608.67	609.14
4	441	453.3	408.82	411.61	415.60
5	245	235.7	236.54	239.64	242.72
6	135	102.1	122.49	124.09	125.17
7	42	37.9	58.12	58.44	58.20
8	17	12.3	25.68	25.45	24.76
9	11	3.6	10.70	10.41	9.75
10+	11	1.1	4.47	5.69	5.42
Total:	3205				
Chi-square		----	34.52	27.49	25.52
P_{χ^2}		0	<0.001	<0.01	<0.01
d.f. = 9					

* NB = Negative binomial
NTA = Neyman type A
PB = Poisson binomial for n=2

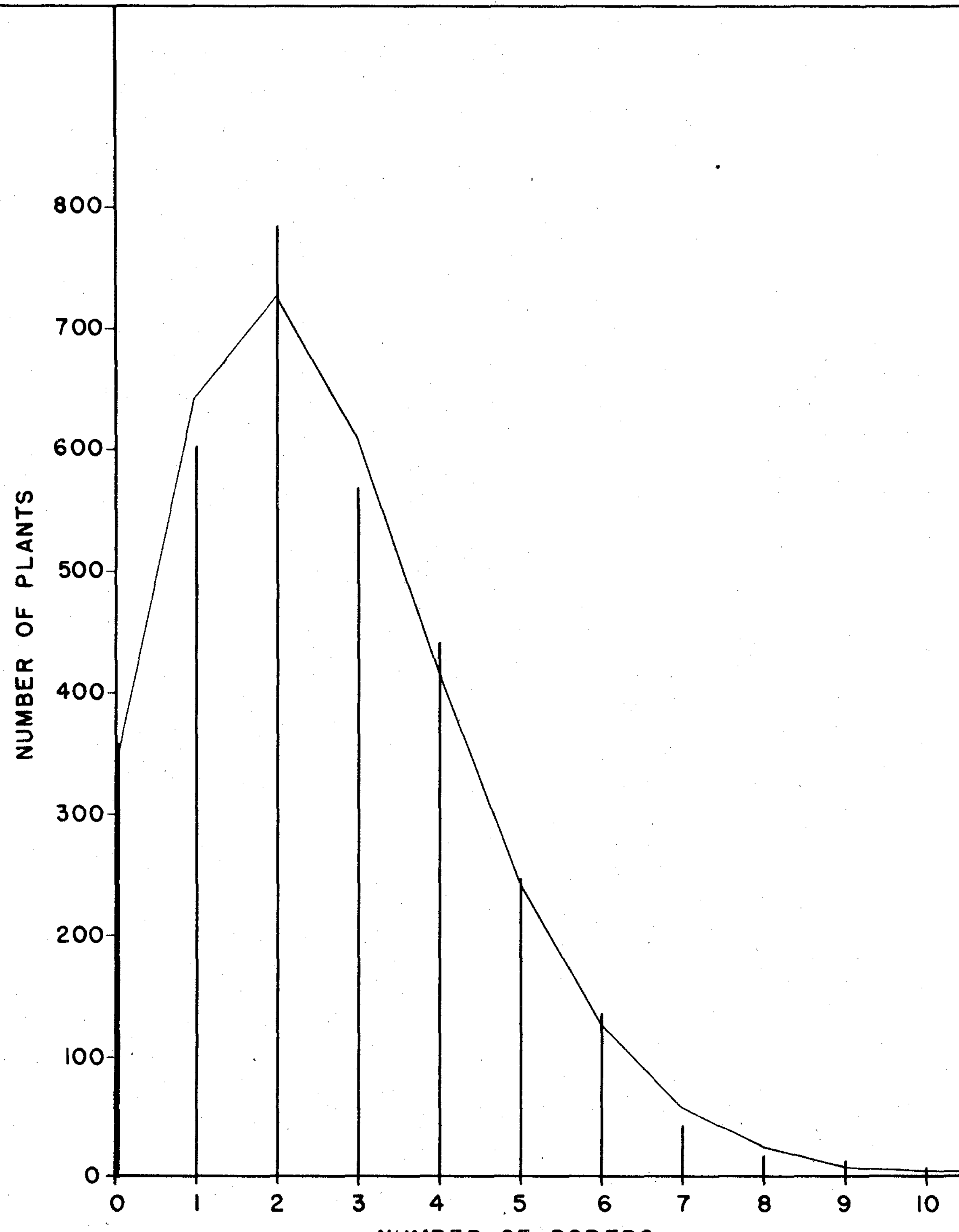

Figure 1. Bar graph showing observed frequencies of total borers per plant from experimental area number one and frequency polygon showing expected frequencies from Poisson binomial distribution.

Table 2.

Experimental area number 1, pupae and fifth instar larvae.

Observed and theoretical frequencies; the values of chi-square and their attached probability

Observed		Theoretical		
x	f_x	NB*	NTA*	PB(n=2)*
0	588	553.85	568.14	587.85
1	807	845.72	829.36	799.38
2	741	750.81	742.53	741.12
3	479	506.58	509.95	515.08
4	328	287.83	293.57	299.67
5	159	145.14	148.37	150.76
6	67	67.01	67.71	67.74
7	22	28.89	28.43	27.64
8	5	11.80	11.13	10.39
9	7	4.61	4.11	3.63
10+	2	2.76	1.92	1.74
Total:	3205			
Chi-square		15.48	10.02	7.07
P_{x^2}		0.035	0.187	0.420
d.f. = 7				

* NB = Negative binomial
NTA = Neyman type A
PB = Poisson binomial for n=2

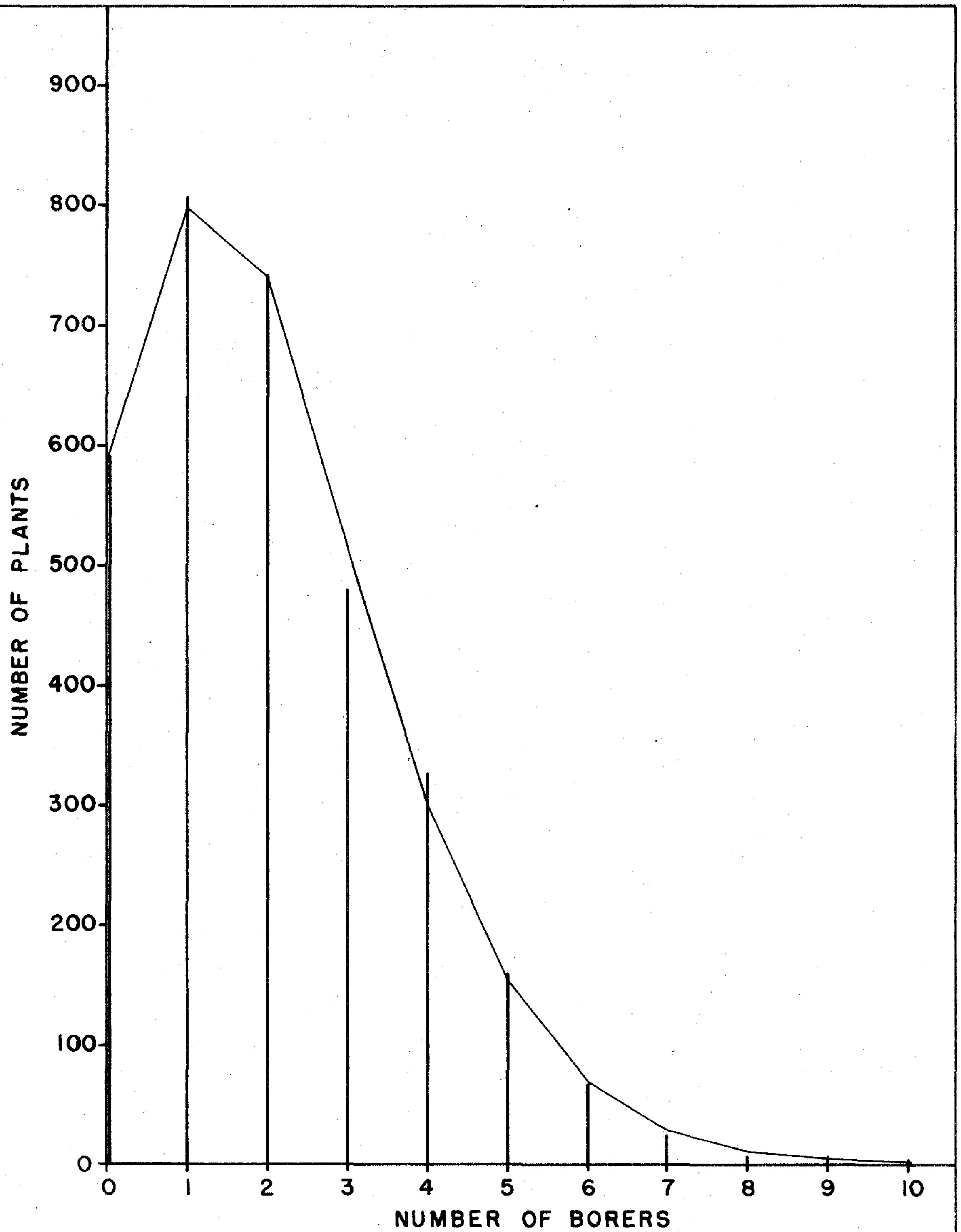

Figure 2. Bar graph showing observed frequencies of pupae and fifth instar larvae per plant from experimental area number one and frequency polygon showing expected frequencies from Poisson binomial distribution.

Table 3.

Experimental area number 1, total borers per plot.

Observed and theoretical frequencies; the values of chi-square and their attached probabilities.

Observed		Theoretical	
x	f_x	NB*	NTA*
0	0	0.00	0.01
1	0	0.00	0.03
2	0	0.02	0.08
3	0	0.05	0.16
4	0	0.12	0.29
5	1	0.26	0.50
6	1	0.49	0.80
7	1	0.84	1.20
8	0	1.34	1.71
9	5	2.01	2.36
10	2	2.85	3.12
11	5	3.84	4.01
12	6	4.97	4.99
13	8	6.21	6.06
14	3	7.50	7.18
15	7	8.81	8.32
16	15	10.08	9.44
17	12	11.25	10.50
18	10	12.30	11.48
19	10	13.19	12.35
20	12	13.89	13.07
21	11	14.38	13.63
22	14	14.67	14.01
23	11	14.75	14.21
24	13	14.64	14.24
25	17	14.35	14.09
26	17	13.90	13.79
27	15	13.33	13.35
28	15	12.65	12.78
29	18	11.89	12.11

Table 3. (Continued)

Observed		Theoretical	
x	f_x	NB*	NTA*
30	8	11.08	11.37
31	11	10.24	10.58
32	6	9.39	9.75
33	8	8.54	8.91
34	9	7.72	8.07
35	5	6.92	7.26
36	9	6.17	6.47
37	7	5.47	5.73
38	7	4.82	5.03
39	3	4.22	4.39
40	4	3.68	3.81
41	1	3.19	3.28
42	5	2.75	2.80
43	2	2.36	2.38
44	3	2.02	2.01
45	0	1.72	1.69
46	1	1.46	1.41
47	0	1.23	1.17
48	2	1.03	0.96
49	0	0.87	0.79
50	1	0.72	0.65
51	0	0.60	0.53
52	1	0.50	0.42
53	0	0.41	0.34
54	0	0.34	0.27
55	0	0.28	0.22
56	1	0.23	0.17
57	0	0.19	0.14
58	0	0.15	0.11
59	1	0.12	0.08
60+	0	0.99	3.34
Total:	324		
Chi-square		17.03	16.22
P_{x^2}		0.843	0.877
d.f. = 24			

* NB = Negative binomial
NTA = Neyman type A

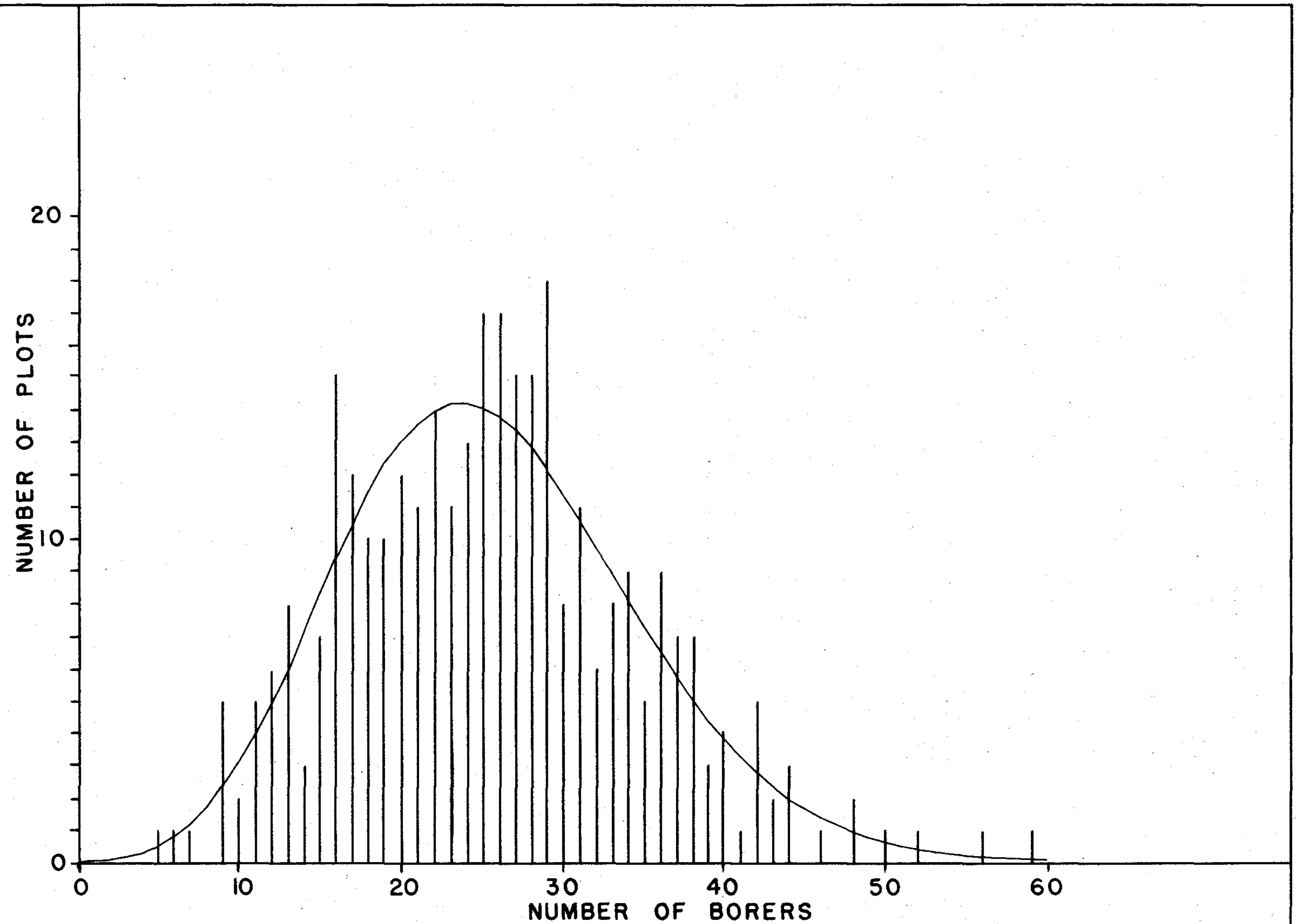

Figure 3. Bar graph showing observed frequencies of total borers per plot from experimental area number one and frequency polygon showing expected frequencies from Neyman type A distribution.

Table 4.

Experimental area number 2, total borers per plant.

Observed and theoretical frequencies; the values of chi-square and their attached probabilities.

Observed		Theoretical	
x	f_x	NB*	NTA*
0	423	426.60	419.40
1	414	406.36	405.33
2	253	248.65	257.06
3	117	123.91	128.39
4	53	54.71	54.70
5	22	22.30	20.75
6	4	8.58	7.15
7	4	3.16	2.29
8	3	1.13	0.69
9	2	0.39	0.20
10	0	0.21	0.07
Total:	1296		
Chi-square		0.71	2.63
P_{χ^2}		0.952	0.798
d.f. = 5			

* NB = Negative binomial
NTA = Neyman type A

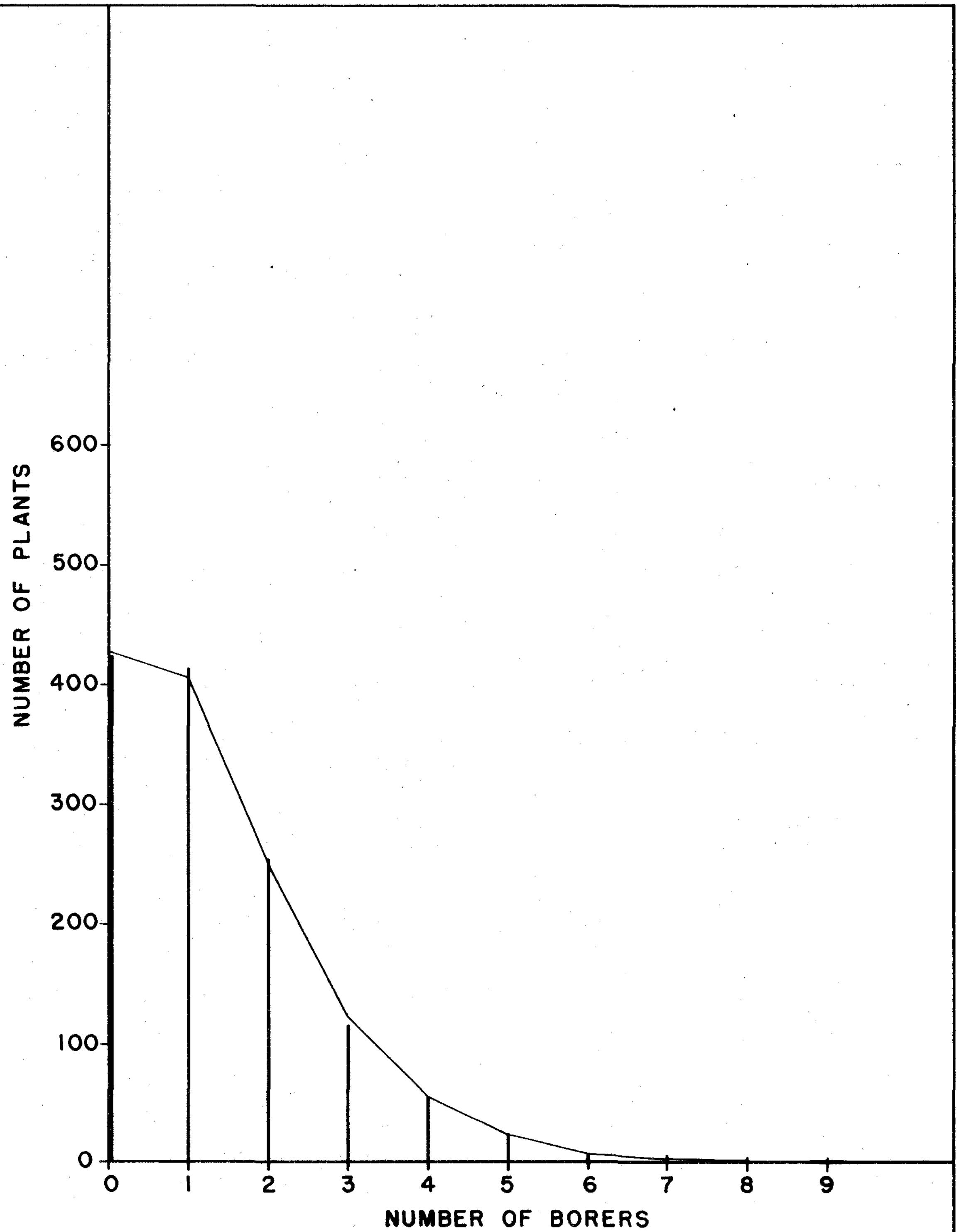

Figure 4. Bar graph showing observed frequencies of total borers per plant for experimental area number two and frequency polygon showing expected frequencies from negative binomial distribution.

Table 5.

Experimental area number 2, total borers per plot.

Observed and theoretical frequencies; the values of chi-square and their attached probabilities.

Observed		Theoretical	
x	f_x	NB*	NTA*
0	10	8.92	12.41
1	18	22.96	23.14
2	39	35.37	33.50
3	33	42.32	39.74
4	42	43.34	41.41
5	56	39.92	39.16
6	36	34.01	34.28
7	26	27.31	28.17
8	19	20.92	21.94
9	19	15.42	16.32
10	7	11.02	11.65
11	4	7.66	8.03
12	4	5.21	5.06
13	4	3.47	3.47
14	2	2.27	2.19
15	1	1.47	1.35
16	2	0.94	0.81
17	1	0.59	0.48
18	0	0.20	0.28
19	0	0.12	0.16
20	0	0.08	0.09
21	0	0.05	0.05
22	0	0.03	0.03
23	0	0.02	0.01
24	0	0.01	0.01
25	1	0.01	0.01
26	0	0.40	0.00
Total:	324		
Chi-square		17.18	18.97
P_{x^2}		0.103	0.062
d.f. = 11			

* NB = Negative binomial
NTA = Neyman type A

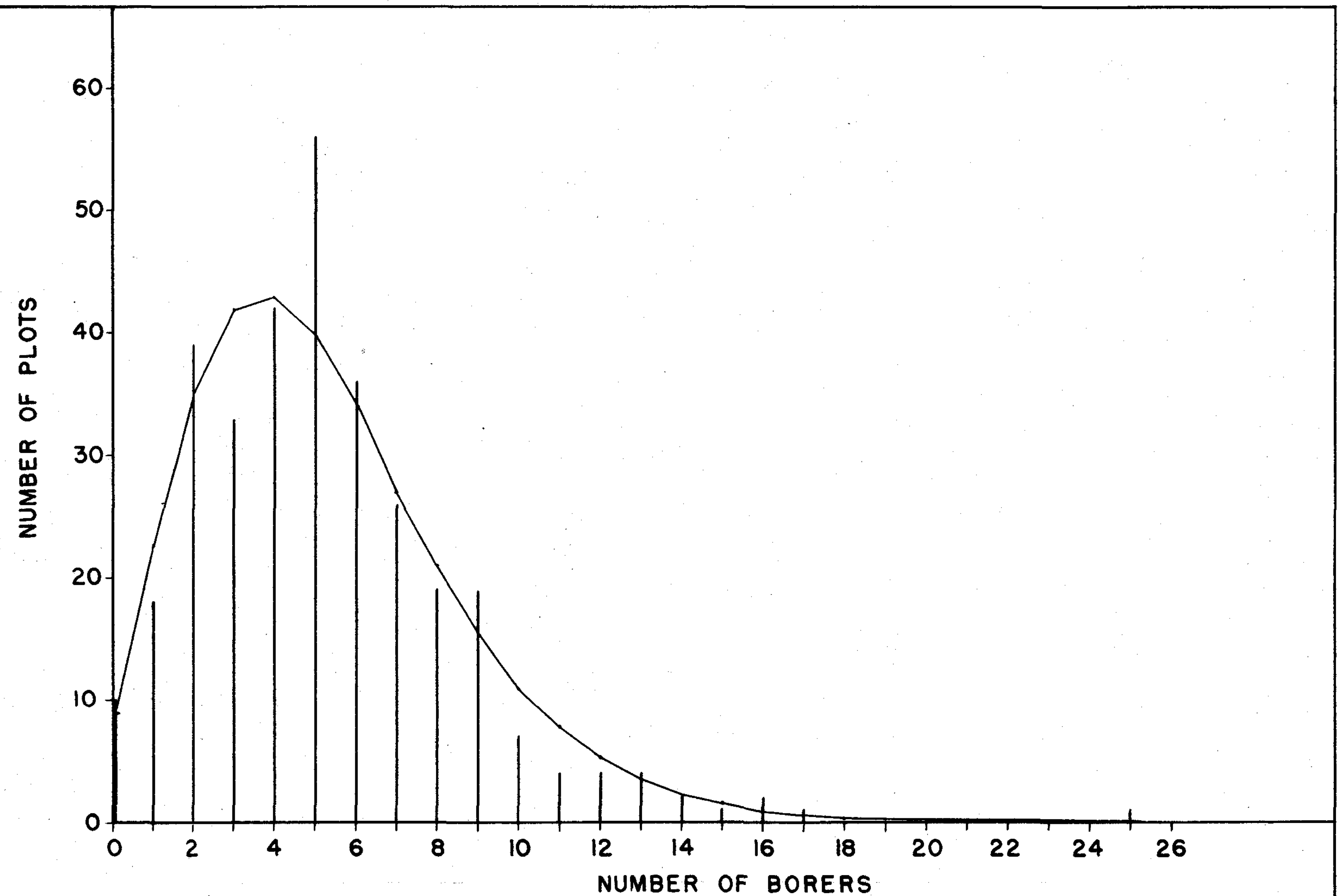

Figure 5. Bar graph showing observed frequencies of total borers per plot for experimental area number two and frequency polygon showing expected frequencies from negative binomial distribution.

been any better. The frequency distribution of borers per plot for area number three was fitted best by the negative binomial, see Table 7 and Figure 7. On the other hand, the frequency distribution of borers per plant was fitted best by the Poisson binomial, see Table and Figure 6. Both frequency distributions for area number four were well fitted by the Poisson binomial, see Tables and Figures 8 and 9.

In most cases the difference between the various distributions is slight. The statement that one distribution fits better than any of the others is based on the value of chi-square and its attached probability.

Both the negative binomial and Neyman type A were fitted to all nine frequency distributions. The Poisson binomial was fitted to five of the nine distributions. In all five cases where the Poisson binomial was fitted it gave the best fit. The negative binomial fit best in three cases while the Neyman type A gave the best fit in only one instance. The fitting does indicate that the Poisson binomial and the negative binomial are the appropriate graduating curves in that order. An interesting question presenting itself is whether or not sampling a population of corn borer larvae enhances the skewness of the resulting frequency distribution and thus makes the negative binomial the appropriate distribution.

Table 6.

Experimental area number 3, total borers per plant.

Observed and theoretical frequencies; the values of chi-square and their attached probabilities.

Observed		Theoretical		
x	f_x	NB*	NTA*	PB(n=2)*
0	907	902.85	900.89	904.44
1	275	288.86	288.76	279.42
2	88	78.07	82.00	89.09
3	23	19.81	19.34	18.63
4	3	4.86	4.07	3.70
5	0	1.56	0.95	0.61
Total:	1296			
Chi-square		1.94	1.24	0.61
P_{χ^2}		0.385	0.535	0.740
d.f. = 2				

* NB = Negative binomial
NTA = Neyman type A
PB = Poisson binomial (n=2)

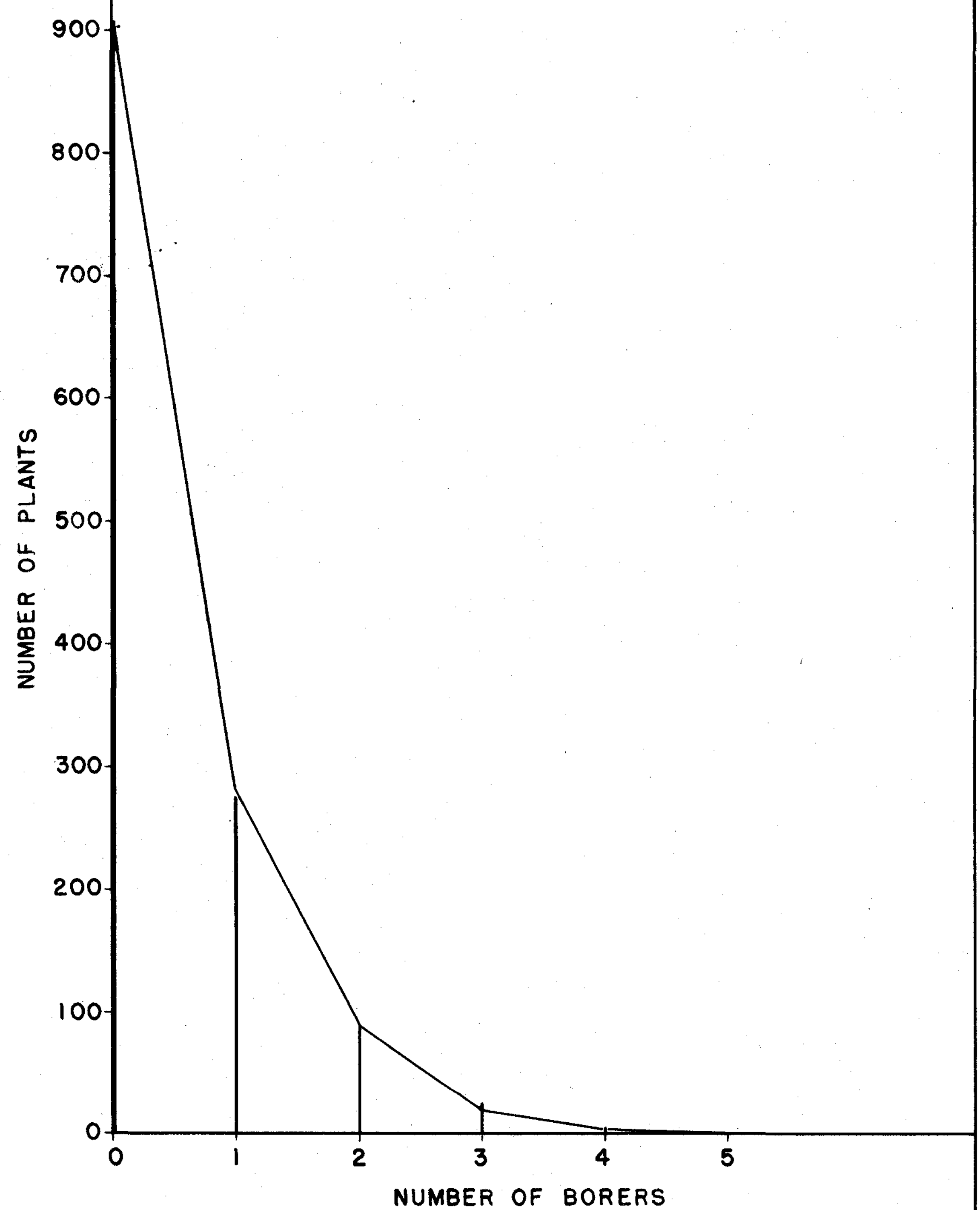

Figure 6. Bar graph showing observed frequencies of total borers per plant for experimental area number three and frequency polygon showing expected frequencies from Poisson binomial distribution.

Table 7.

Experimental area number 3, total borers per plot.

Observed and theoretical frequencies; the values of chi-square and their attached probabilities.

Observed		Theoretical	
x	f_x	NB*	NTA*
0	89	89.53	89.01
1	96	91.85	88.63
2	57	64.34	66.29
3	44	38.10	40.41
4	16	20.49	21.53
5	11	10.36	10.38
6	7	5.01	4.62
7	3	2.34	1.93
8+	1	1.98	1.20
Total:	324		
Chi-square		3.26	5.05
P_{χ^2}		0.658	0.410
d.f. = 5			

* NB = Negative binomial
NTA = Neyman type A

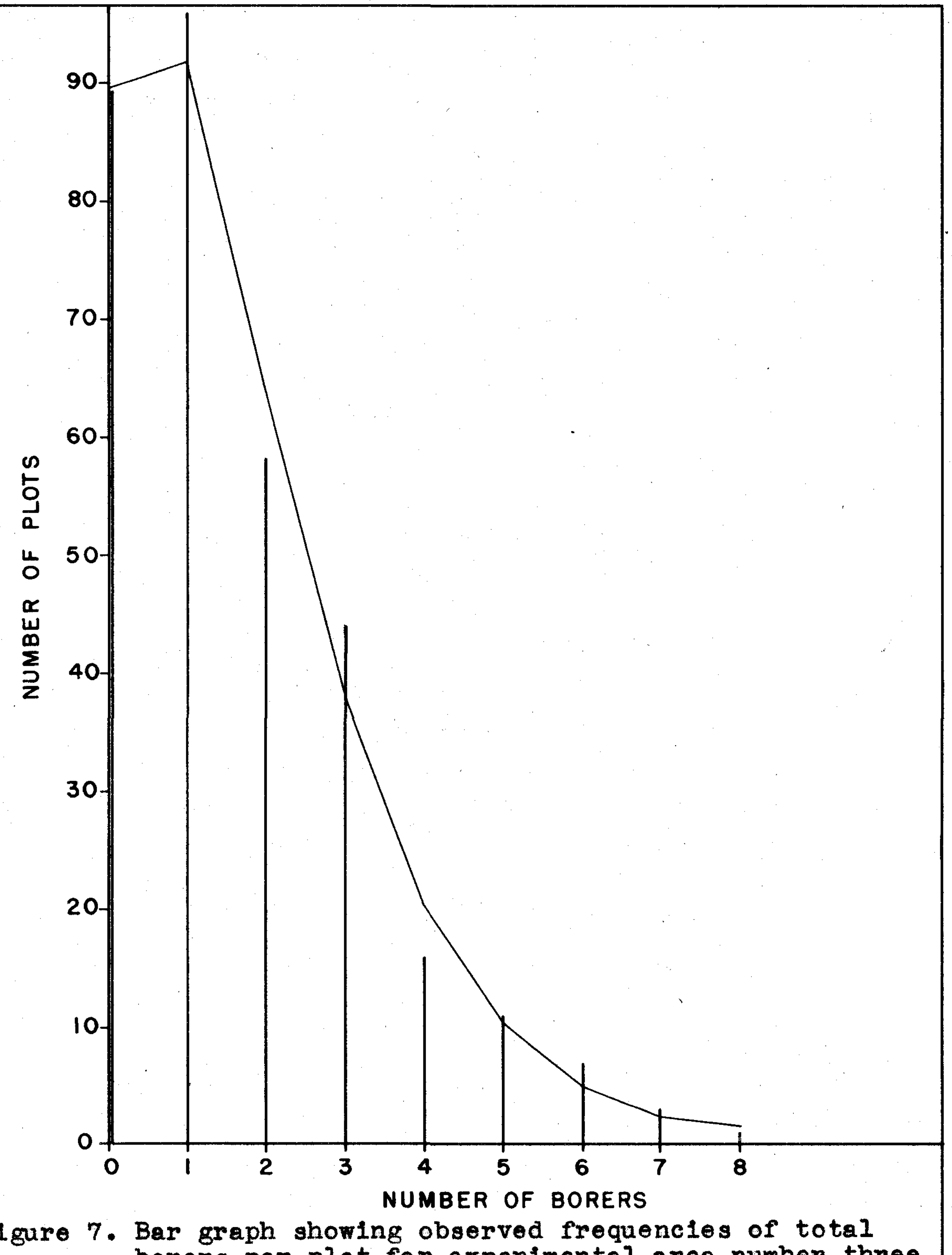

Figure 7. Bar graph showing observed frequencies of total borers per plot for experimental area number three and frequency polygon showing expected frequencies from negative binomial distribution.

Table 8.

Experimental area number 4, total borers per plant.

Observed and theoretical frequencies; the values of chi-square and their attached probabilities.

Observed		Theoretical		
x	f_x	NB*	NTA*	PB(n=2)*
0	1117	1114.98	1116.97	1116.39
1	149	154.51	150.44	150.47
2	27	22.51	24.75	26.21
3	3	3.99	3.84	2.92
Total:	1296			
Chi-square		1.35	0.40	0.05
P_{x^2}		0.510	0.820	0.980
d.f. = 2				

* NB = Negative binomial
NTA = Neyman type A
PB = Poisson binomial (n=2)

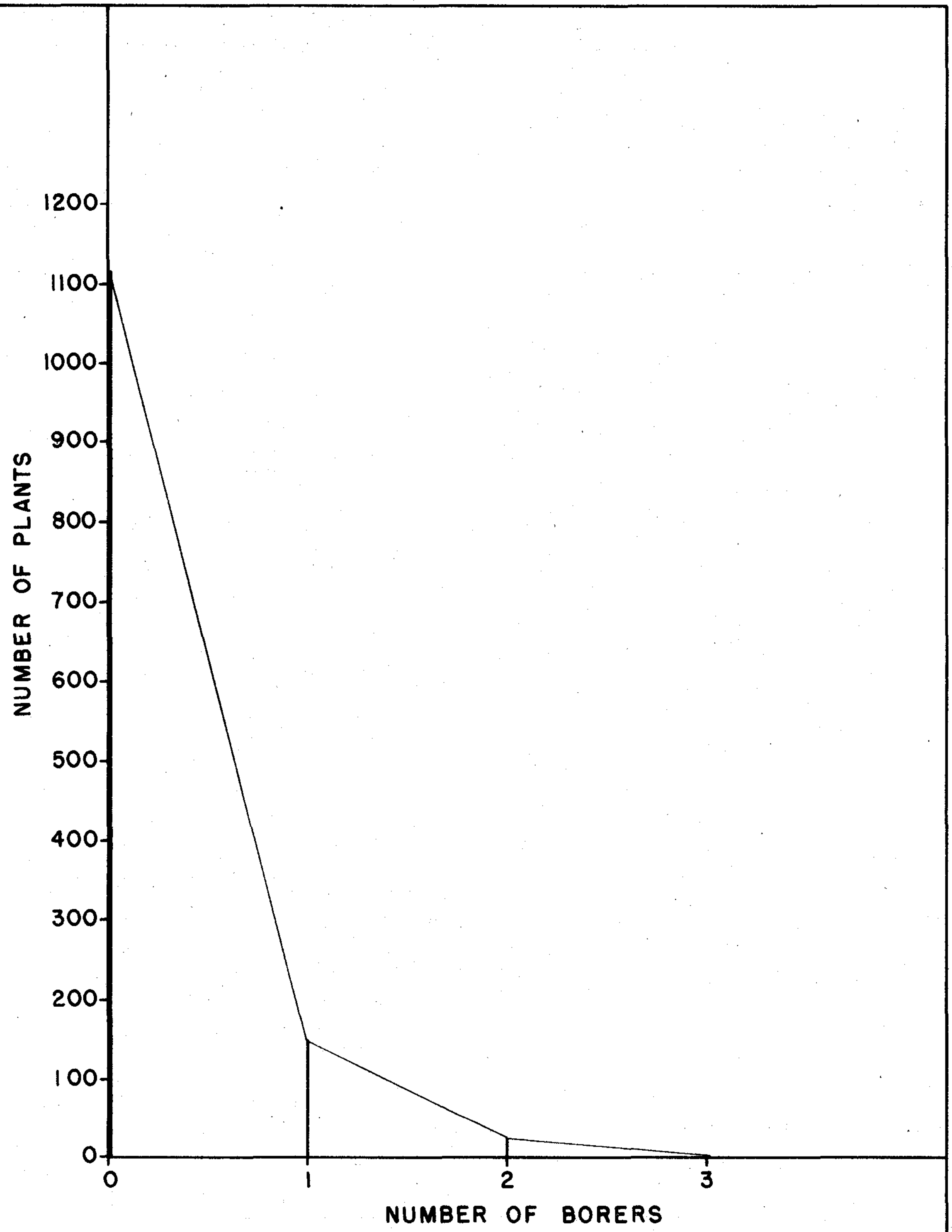

Figure 8. Bar graph showing observed frequencies of total borers per plant for experimental area number four and frequency polygon showing expected frequencies from Poisson binomial distribution.

Table 9.

Experimental area number 4, total borers per plot.

Observed and theoretical frequencies; the values of chi-square and their attached probabilities.

Observed		Theoretical		
x	f_x	NB*	NTA*	PB(n=2)*
0	188	185.79	187.99	197.02
1	83	89.28	85.02	84.34
2	36	32.99	34.52	37.45
3	14	10.97	11.65	11.17
4	2	3.45	3.51	3.11
5	1	1.04	0.97	0.72
6	0	0.48	0.33	0.19
Total:	324			
Chi-square		2.36	1.28	1.06
P_{χ^2}		0.505	0.735	0.785
d.f. = 3				

* NB = Negative binomial
NTA = Neyman type A
PB = Poisson binomial (n=2)

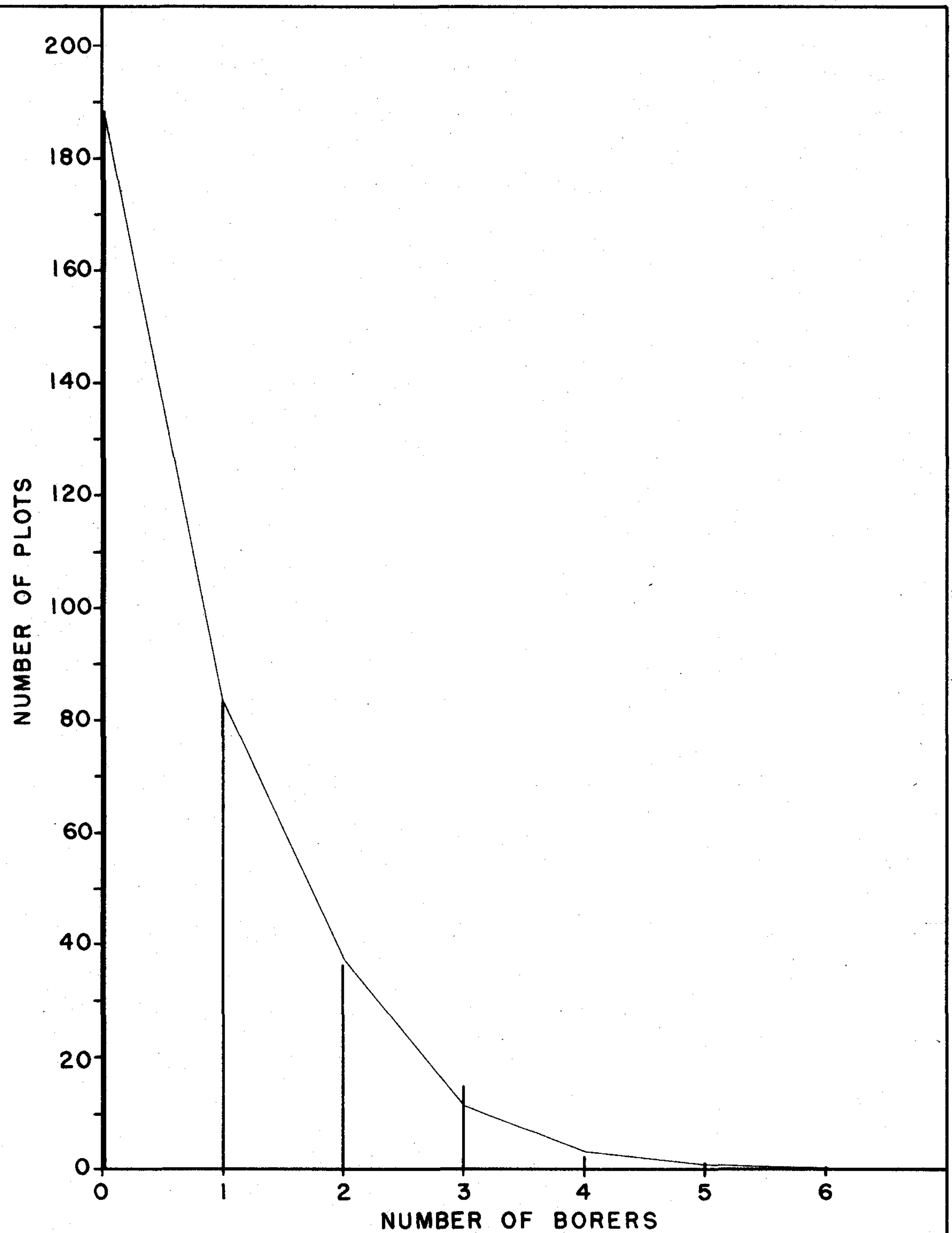

Figure 9. Bar graph showing observed frequencies of total borers per plot for experimental area number four and frequency polygon showing expected frequencies from Poisson binomial distribution.

The Use of Transformations on Non-normal Data when Using the Analysis of Variance

The use of transformations has been adequately discussed, in general, by Bartlett (7) and Kempthorne (23), and in particular, by Beall (11) with regard to experiments with insect populations.

A transformation is used, in an analysis of variance, whenever it is known that the data which are to be analyzed are non-normal, or do not in some other way satisfy the assumptions listed by Eisenhart (17). By using a transformation some of the consequences of not satisfying these assumptions, Cochran (15), may be avoided or at least minimized. The transformation will change the scale of measurement and may make the analysis more valid.

There are three general types of transformations:

(1) The logarithmic transformation used on multiplicative relationships.

(2) A transformation which will stabilize the variance and which may or may not give normality. It is hoped that deviations from additivity on the transformed scale are small.

(3) The probit or logit transformations, used in biological assay, which do not stabilize the variance.

Kendall (24) outlines the theory which leads to those transformations included under (2) above.

Suppose a transformed variate x' is wanted which is a function of x, $x'(x)$. Then as an approximation

$$\mathrm{var}(x') = \left(\frac{dx'}{dx}\right)^2 \mathrm{var}\ x .$$

If the variance of x is related to the mean so that var(x) = f(m), where m is the mean, then

$$\mathrm{var}(x') = \left(\frac{dx'}{dx}\right)^2 f(m)$$

and if x varies about m by small quantities, as a further approximation,

$$\mathrm{var}(x') = \left(\frac{dx'}{dx}\right)^2 f(x) .$$

Now since a constant variance, λ say, is required,

$$\frac{dx'}{dx} = \sqrt{\frac{\lambda}{f(x)}}$$

which on being integrated gives

$$x' = \int \sqrt{\frac{\lambda}{f(x)}}\, dx . \tag{1}$$

In Entomology three transformations belonging to group (2) above are particularly useful. These transformations are: (1) the square root transformation for Poisson data, (2) the arc sine transformation for binomial data, and (3) the inverse hyperbolic sine transformation for contagious data. Since in the present investigation it has been established that the data are contagious, the inverse hyperbolic sine transformation of Beall and a new square root transformation will be examined.

The inverse hyperbolic sine transformation

Beall (11) assumed that the mean and the variance were related in the following way:

(2) $$\mu_2 = \mu_1' + \lambda(\mu_1')^2 \quad .$$

On substituting $(x + \lambda x^2)$ for $f(x)$ in (1) and integrating, the inverse hyperbolic sine transformation results

(3) $$x' = \lambda^{-\frac{1}{2}} \sinh^{-1} (\lambda x)^{\frac{1}{2}}$$

which gives the square root transformation if $\lambda = 0$, and approaches $\log(x+1)$ as λx increases.

It can be easily shown that the variance of any of the three distributions under study will satisfy equation (2) where λ is the inverse of the main parameter, i.e., $\underline{k}$ for the negative binomial, $\underline{m}_1$ for the Neyman type A, $\underline{a}$ for the Poisson binomial.

The contagious square root transformation

In all the distributions under study the variance is related to the mean in the following way, equations (5, 24, 52) appendix B:

$$\text{Var} = \text{Mean}(1 + \lambda')$$

where λ' is now the secondary parameter in any of the three distributions under investigation. On substituting $x(1+\lambda')$ in equation (1) and integrating, the square root transformation for contagious distributions results.

$$x' = \sqrt{x/(1 + \lambda')} \quad . \tag{4}$$

The use of either transformation poses the problem of estimating the transformation parameters from the data. Beall (11) has suggested that λ be estimated from two plots selected at random within each block and treated alike. Anscombe (1) points out that for moderate values of the mean the number of plots treated alike should be at least nine. Such a procedure will be unacceptable to the research entomologist testing insecticides under natural conditions with mechanical equipment since the plots must be large.

A suggested procedure, which will be investigated in detail, would be to use the individual plant data to estimate the required parameter, for each treatment, and use the transformed plant data to form plot totals to be used in the analysis.

For this purpose the parameters are estimated from the following relations:

$$\begin{aligned} \lambda &= (s^2 - \bar{x})/\ \bar{x}^2 \\ \lambda' &= (s^2 - \bar{x})/\ \bar{x} \quad . \end{aligned} \tag{5}$$

The inverse hyperbolic sine transformation uses λ as above but the quantity used in the square root transformation is not λ' but $(1+\lambda')$. It can be seen from equation (5) above that

$$1+\lambda' = s^2/\bar{x}$$

which is the amount by which the variance of the contagious distribution exceeds that of the Poisson.

Results

It was of interest to find out if the transformations would stabilize the variance and as a matter of curiosity their effect on the normality of the data. In order to do this the frequency distributions of borers per plant were chosen for two reasons, (1) sampling procedures are always used so that the plant is the sampling unit, (2) the use of three insecticides could be simulated by letting the high density experimental area be the check and assuming three insecticides of increasing effectiveness on the experimental areas with the decreasing densities. The large sample estimates of the population parameters were used to calculate the transformation parameter needed in each case.

Table 10 gives the values of the mean and variance of all four experimental areas for the original data and their transformed values using both transformations. If the population mean is as low as 1.3 both transformations are equally effective in stabilizing the variance. With population means less than 1.0 both transformations give an increasingly smaller variance but the square root transformation does have a smaller range over the four experimental areas studied. In the absence of Beall's tables, which are not as widely distributed as could be hoped, the actual calculation of the

Table 10.

Comparison of the means and variances of the original data with the variances of data transformed by the inverse hyperbolic sine and square root transformations. Total borers per plant.*

	Untransformed		Variance of transformed data	
Area no.	Mean	Var.	$\sinh^{-1}$	Square root
1	2.032	2.704	0.421	0.379
2	1.307	1.856	0.389	0.362
3	0.410	0.512	0.228	0.236
4	0.164	0.192	0.104	0.120

* The frequency distribution of pupae and fifth instar borers was used from experimental area number 1.

transformed values using the inverse hyperbolic sine transformation is not a simple process. The square root transformation for contagious data will find greater applicability since it is much easier to calculate and requires no special tables.

The values of Pearson's β coefficients are commonly used to test for normality since β_1 = zero and β_2 = three for the normal distribution. If the two transformations are in any way successful in imparting normality to the data the values of the β coefficients for the transformed data should approach those for the normal. The values of β_1 and β_2 were calculated for all four experimental areas from the original data and both their transformations. The results are shown in Table 11. Although the transformations do not assure normality they give a satisfactory approximation. In this respect the inverse hyperbolic sine transformation is more successful than the square root transformation for very low values of the mean. For values of the mean above one the square root transformation is more successful.

Efficiency of Size and Shape of Plot

In the design of field experiments with the European corn borer it is helpful to know the efficiency of size and shape of plot in order to have as efficient a design as possible.

Table 11.

The estimated values of β_1 and β_2 for the frequency distributions of borers per plant for all four experimental areas. Original and transformed data using both the inverse hyperbolic sine and square root transformations.

Experimental area	Untransformed		Inverse hyperbolic sine transformation		Square root transformation	
	β_1	β_2	β_1	β_2	β_1	β_2
1	0.808	3.923	0.377	2.521	0.193	2.498
2	2.312	6.573	0.048	1.763	0.000	2.032
3	3.474	6.336	1.013	2.244	1.187	2.575
4	8.455	11.988	1.659	3.874	5.048	6.439

Field plot techniques with insect data have not been studied to any great extent. Beall (9) investigated the use of stratified sampling with data on the Colorado Potato Beetle <u>Leptinotarsa</u> <u>decemlineata</u> (Say.).

In the field of agronomy extensive work has been done with plot techniques. The most quoted is that of H. Fairfield Smith (30) who studied the effect of soil heterogeneity on wheat yields. He found that shape of plot had no effect on his results and developed the following empirical law used in the design of agronomic experiments:

$$V_x = V_1 / x^{b'} \tag{6}$$

where V_x = the variance per unit plot of a plot with x unit plots

V_1 = the variance of a unit plot

x = the number of unit plots in the larger plots

b' = a factor depending on soil heterogeneity

Smith also investigated the relationship of the variance of plots of $\underline{x}$ units within blocks of $\underline{n}$ plots. This variance is,

$$(V_x)_{\frac{n}{x}} = \frac{(V_1)_\infty \quad \dfrac{n(n^b - x^b)}{n^b(n - x)}}{x^b} \tag{7}$$

where $(V_x)_{\frac{n}{x}}$ = the variance of a plot with $\underline{x}$ unit plots in blocks with $\underline{n}$ plots

$(V_1)_\infty$ = the variance per unit plot for an infinite field

$\underline{n}$ = the number of plots per block

b = a factor depending on soil heterogeneity for the infinite field .

The efficiency of a randomized block experiment having $\underline{m}$ plots per block relative to one having $\underline{n}$ plots per block is given by

$$(8) \qquad (V_x)_n / (V_x)_m = n(m-1)(1-n^{-b})/m(n-1)(1-m^{-b}) \; .$$

For experiments with contiguous plots the minimum cost per unit of information is achieved when

$$(9) \qquad x = bK_1/(1-b)K_2$$

where K_1 is the proportion of the total cost proportional to the number of plots, K_2 is the proportion of the total cost proportional to the total area of the experiment, x is as in equation (6), and b as in equation (7).

If guard rows are used the minimum cost per unit of information is achieved when

$$(10) \qquad x = b(K_1 + K_gA)/(1-b)(K_2 + K_gB)$$

where K_g = cost proportional to the area in guard rows

A = the area in guard rows around the plot

B = the width of plot plus guard, minus width of plot, divided by the width of plot.

Conners (16) investigated field plot techniques for sweet potatoes and came to the conclusion that the optimum plot size predicted by Smith's equation differed to some extent from that estimated from the data.

Taylor (32) investigated the effect of correlations in three directions on the shape of the plots. He developed a formula analogous to Smith's with an extra term which takes into account the shape of the plot. The correlations in the three directions, however, have to be computed from the data, which reduces the applicability of the equation since the correlations must be known prior to the design of the experiment.

In investigating the efficiency of shape and size of plot for European corn borer data Smith's work was followed. The variances per unit plot, for 65 of the configurations which used the total area, are presented in Table 12. Since the variances indicated that plot shape might have some effect on the value of the variance, a weighted multiple regression was fitted to the logarithms of the variances using the ratio l/w as a shape factor, where l = the length of row and w = the width in terms of rows. The weights used were directly proportional to the degrees of freedom of each variance. The equation fitted was:

$$(11) \qquad \ln(V_x) = \ln(V_1) - b_1 \ln(x) + b_2 \ln(l/w)$$

for which the following constants were computed:

$$(12) \qquad \ln(V_x) = 0.238 - 0.851 \ln(x) + 0.0103 \ln(l/w) .$$

Table 12.

Variance per unit plot for different sizes and shapes of plots for the corn borer data from experimental area number 1.

No.plots	Shape R H	d.f.	SS	Var. per unit plot
1	1x1	1943	2529.88	1.3020
2	1x2	971	2772.11	0.7138
	2x1		2635.81	0.6787
3	3x1	647	2995.61	0.5144
	1x3		2863.63	0.4917
4	4x1	485	2822.89	0.3637
	2x2		3090.09	0.3982
6	6x1	323	2790.73	0.2400
	3x2		3132.34	0.2694
	2x3		3355.70	0.2886
	1x6		3219.06	0.2768
8	4x2	245	3988.96	0.2544
9	9x1	215	2659.17	0.1527
	3x3		3249.11	0.1866
	1x9		3658.47	0.2101
12	12x1	161	3079.68	0.1328
	6x2		3272.03	0.1411
	4x3		3487.23	0.1504
	2x6		3615.02	0.1559
18	18x1	107	2829.64	0.08161
	9x2		3321.67	0.09581
	6x3		3739.43	0.1079
	3x6		3532.20	0.1019
	2x9		4060.67	0.1171
	1x18		4309.53	0.1243
24	12x2	80	3550.31	0.07704
	4x6		3469.39	0.07528

Table 12. (Continued)

No.plots	Shape R H	d.f.	SS	Var. per unit plot
27	9x3	71	3963.09	0.07656
	3x9		3865.44	0.07468
	1x27		5576.09	0.1077
36	36x1	53	3312.17	0.04821
	18x2		3454.19	0.05028
	12x3		4635.31	0.06748
	6x6		3703.29	0.05391
	4x9		3552.65	0.05171
	2x18		5203.36	0.07575
54	18x3	35	4194.73	0.04110
	9x6		3560.69	0.03488
	6x9		4408.28	0.04319
	3x18		4735.12	0.04639
	2x27		6327.30	0.06199
	1x54		7245.14	0.07098
72	36x2	26	3757.30	0.02787
	12x6		4529.95	0.03360
	4x18		3919.26	0.02907
81	9x9	23	4683.81	0.03103
	3x27		4897.48	0.03245
108	36x3	17	5524.17	0.02785
	18x6		4038.11	0.02036
	12x9		5475.46	0.02761
	6x18		5324.86	0.02685
	4x27		4290.98	0.02163
	2x54		8672.36	0.04373
162	18x9	11	5289.78	0.01832
	9x18		5508.82	0.01908
	6x27		6129.61	0.02123
	3x54		5482.85	0.01899
216	36x6	8	5170.48	0.01385
	12x18		6803.41	0.01822
	4x54		4259.65	0.01141

Table 12. (Continued)

No.plots	Shape R H	d.f.	SS	Var. per unit plot
243	9x27	7	7247.49	0.01753
324	36x9	5	7774.73	0.01481
	18x18		6194.09	0.01180
	12x27		8425.13	0.01605
	6x54		6012.86	0.01145

Since the value of b_2 = 0.0103 it was desirable to test H_0:b_2 = 0 and the following analysis of variance was computed:

Analysis of Variance

Due to	d.f.	SS	MS
Fitting x_1 and x_2	2	1.03461	
Fitting x_1	1	1.03447	
Attributable to x_2	1	0.00014	0.00014
Error	62	0.00938	0.00015
Total	64	1.04399	

Since F = 0.933, with 1 and 62 d.f., the null hypothesis that b_2 = 0 is accepted. The factor for shape does not account for a significant reduction in the sum of squares from regression. As a result the regression on the first variable, size of plot, is used. The computed simple regression equation is:

$$\ln(V_x) = 0.234 - 0.851 \ln(x) \quad (13)$$

The observed values of $\ln(V_x)$ and the computed regression line are shown in Figure 10. The correlation coefficient r =-0.995.

The regression coefficient computed in equation (13) is the b of equation (6). In order to use b' in equation (8) the regression coefficient b for an infinite field had to be estimated. Entering the computed value of b' in Figure 11, which was drawn from Smith (30), the value of b is found to be 0.842.

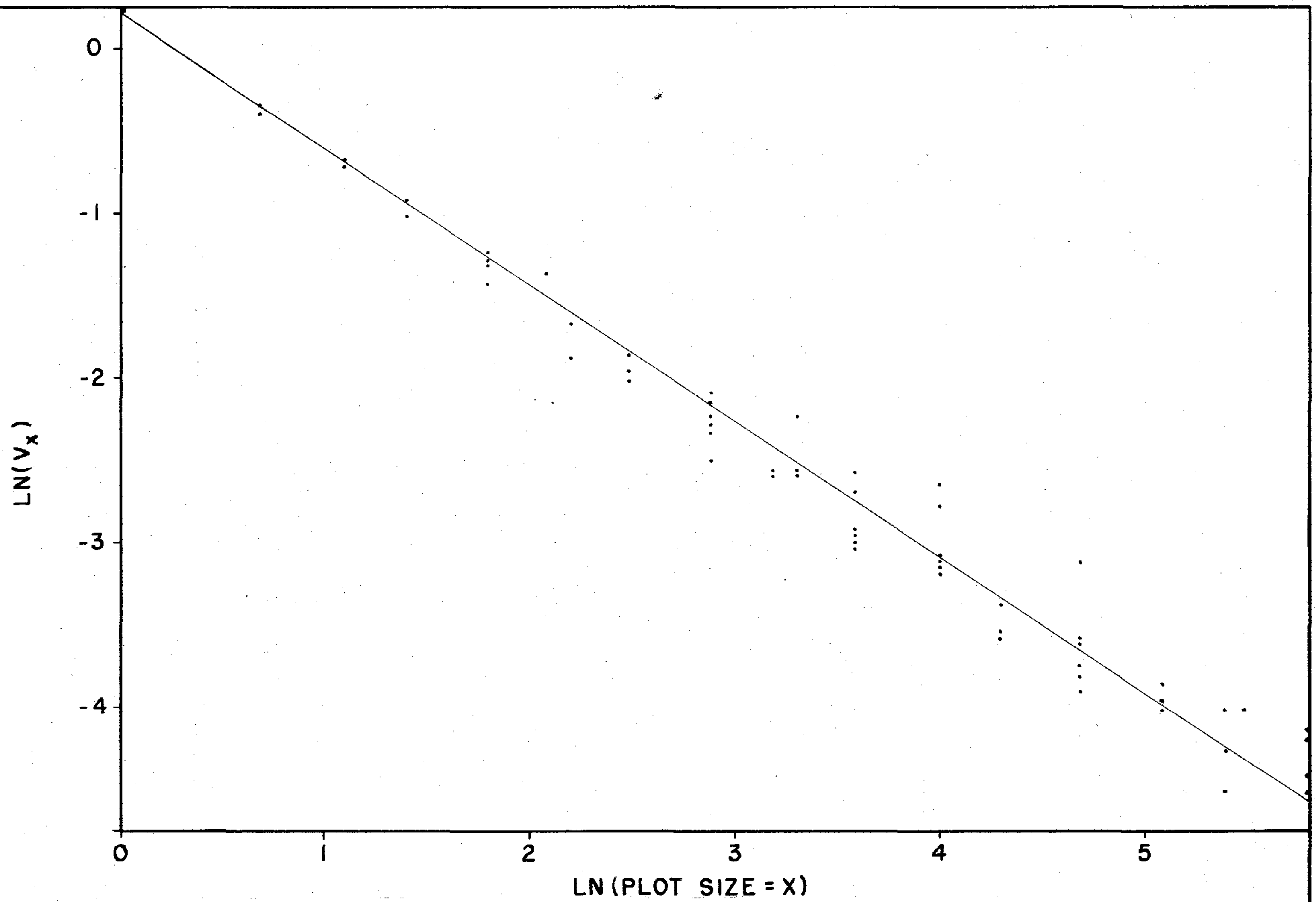

Figure 10. Linear regression of the natural logarithm of the variance of a plot with x unit plots on the natural logarithm of the number of unit plots in the larger plot.

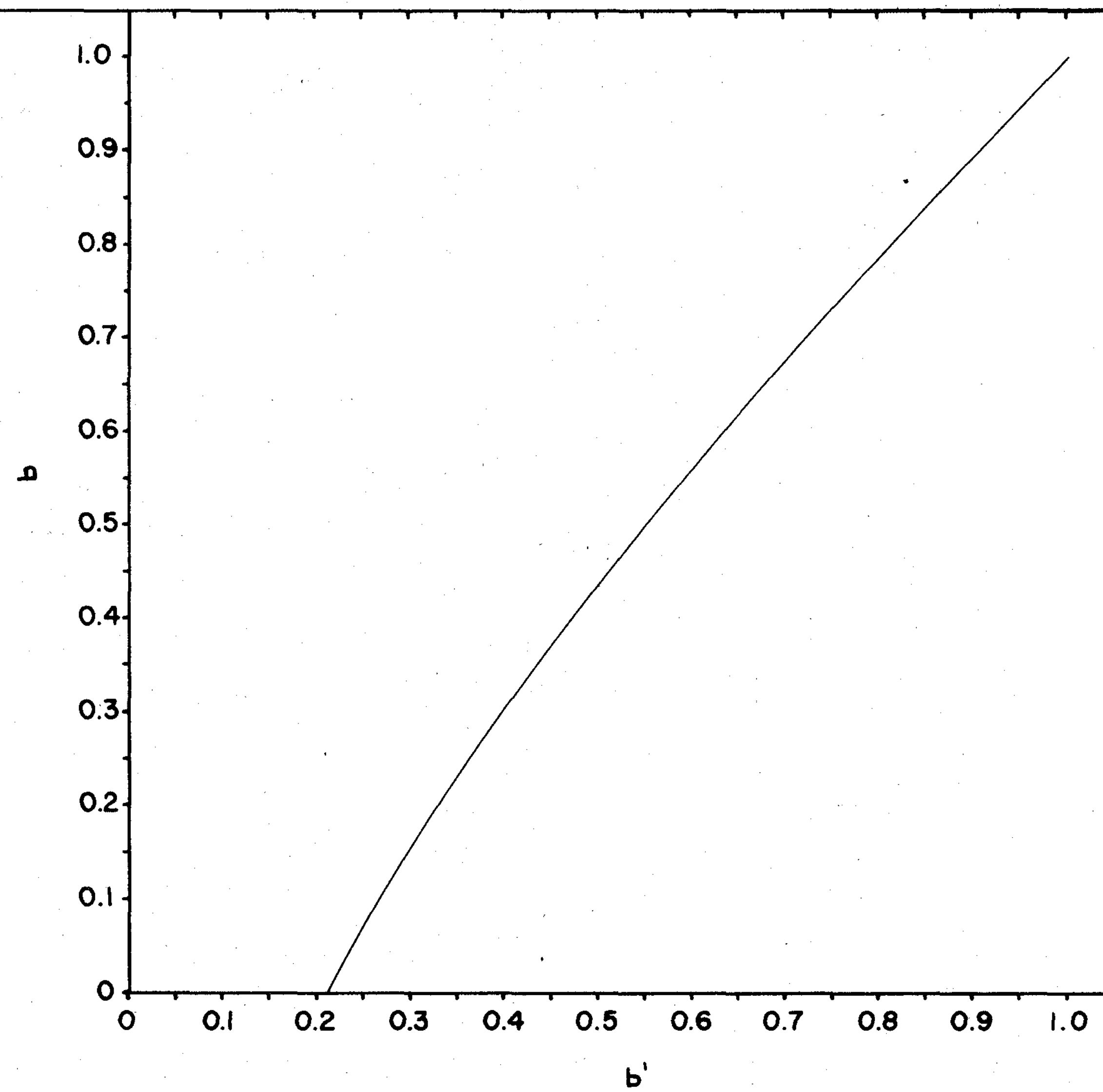

Figure 11. Chart for determining the value of the regression coefficient b, for an infinite field, from the computed value of the regression coefficient b′ for a finite field. From Smith (30).

The relative efficiency of a randomized block experiment having 6 plots per block to one having 9 plots per block is:

$$(14) \qquad (V_x)_9 / (V_x)_6 = 9(5)(1-9^{-0.842})/6(8)(1-6^{-0.842})$$
$$= 37.9260/37.3824$$
$$= 1.0145 \ .$$

From the observed variances, using the shapes with the smallest variances, the same relative efficiency is 0.9965 which agrees satisfactorily with the expected efficiency.

The Sampling of European Corn Borer Populations

It was of interest to determine the number of plants which should be dissected in each plot so that the means of the plots to be used in an analysis of variance would approach some degree of normality.

It has been determined that the larval populations of the European corn borer studied follow one of the three contagious distributions fitted to the data. The sum of $\underline{n}$ independent variables following any one of these contagious distributions is itself distributed contagiously with the appropriate distribution. This can be shown by considering the moment generating function for the negative binomial

$$\phi(t) = \left\{1-(e^t-1)p\right\}^{-k} \ .$$

If there are $\underline{n}$ independent variables following the negative binomial distribution the following relation holds:

$$\phi_n(t) = \phi_1(t)\phi_2(t)\cdots\cdots\phi_n(t)$$
$$= \left[\phi(t)\right]^n ,$$

hence

$$\left[\phi(t)\right]^n = \left\{1-(e^t-1)p\right\}^{-nk} .$$

This property, common to all three distributions, is known as the property of reproduction.

It must also be shown that as the means of the distributions increase the distribution of these means will approach normality.

The approach to normality will be proved by using the following formulae given to the author by Dr. H. O. Hartley. The β coefficients for a mean are given by

$$\beta_1(\bar{x}) = \beta_1/n$$
$$\beta_2(\bar{x}) = 3 + (\beta_2 - 3)/n . \tag{15}$$

The βs for the three contagious distributions investigated are:

(1) Negative Binomial

$$\beta_1 = \frac{p^2(1+3p)}{\bar{x}(1+p)} \qquad \beta_1(\bar{x}) = \frac{p^2(1+3p)}{n\bar{x}(1+p)}$$

$$\beta_2 = 3+\frac{p^2(1+4p)(3+2p)}{\bar{x}(1+p)^2} \qquad \beta_2(\bar{x}) = 3+\frac{p^2(1+4p)(3+2p)}{n\bar{x}(1+p)^2}$$

(2) Neyman Type A

$$\beta_1 = \frac{[1+m_2(3+m_2)]^2}{\bar{x}(1+m_2)^3} \qquad \beta_1(\bar{x}) = \frac{[1+m_2(3+m_2)]^2}{n\bar{x}(1+m_2)^3}$$

$$\beta_2 = 3 + \frac{1+m_2\{7+m_2(6+m_2)\}}{\bar{x}(1+m_2)^2} \qquad \beta_2(\bar{x}) = 3 + \frac{1+m_2\{7+m_2(6+m_2)\}}{n\bar{x}(1+m_2)^2}$$

(3) Poisson Binomial, n = 2

$$\beta_1 = \frac{(1+3p)^2}{\bar{x}(1+p)^3} \qquad \beta_1(\bar{x}) = \frac{(1+3p)^2}{n\bar{x}(1+p)^3}$$

$$\beta_2 = 3 + \frac{(1+7p)}{\bar{x}(1+p)^2} \qquad \beta_2(\bar{x}) = 3 + \frac{(1+7p)}{n\bar{x}(1+p)^2} \quad .$$

As $n \rightarrow \infty$, $\beta_1(\bar{x})$ for all three distributions approaches 0 while $\beta_2(\bar{x})$ approaches 3. For the normal distribution $\beta_1 = 0$, and $\beta_2 = 3$. Therefore all three distributions approach normality assymptotically with increasing n.

The number of plants to be dissected in order to achieve some preassigned approach to normality in the distribution of the means may be determined from Figure 12. A one cycle log log chart does the work of a 3 by 3 cycle chart using the following procedure. Using previously determined values of $\bar{x}$ and p, for say the negative binomial, the value of β_1 and $(\beta_2 - 3)$ are calculated, and whichever is the larger is used to enter the ordinate of Figure 12. From Table 11 (β_2-3) for field number one is 0.923 which is entered on the ordinate. The ordinate scale is mentally shifted down one cycle so that

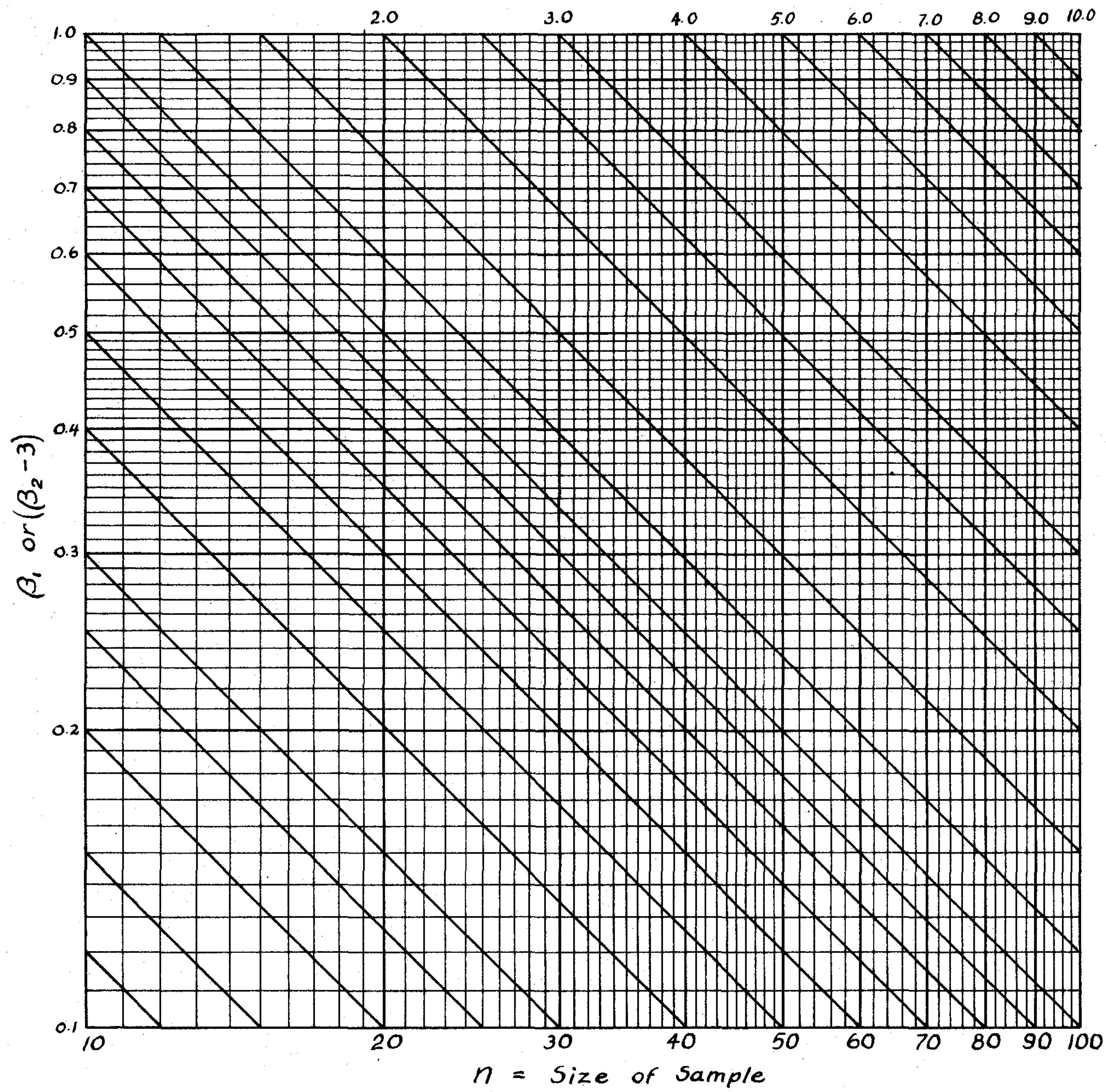

Figure 12. Chart to determine the size of sample required for the plot means to approach normality.

it now reads from 0.1 to 0.01, and being satisfied with an approach to normality on the order of 0.05, the value of n is read on the abcissa. In the present example the value of n = 18.5 or 19 plants. If 19 plants selected at random from each plot are dissected from a population with an average of 2.6 borers per plant, and the plot totals used in the analysis of variance, no transformation will be required.

For low population densities the use of a transformation will result in a substantial decrease in the number of plants which should be dissected. In experimental area number 4, with a mean of 0.16 borers per plant, a sample of 180 plants per plot would be required in order for the distribution of the means to approach normality without a transformation. Using the inverse hyperbolic sine transformation the required sample will be only 34 plants.

CONCLUSIONS

From the analysis of data on the European corn borer from four fields of varying population densities it is concluded that:

1. The European corn borer is contagiously distributed following a Poisson binomial distribution with n=2, although A Neyman type A does graduate the data fairly well as does the negative binomial.

2. Samples from a European corn borer population follow the negative binomial distribution for values of the mean above one. For values of the mean less than one the Poisson binomial is the appropriate distribution.

3. The mortality from each egg mass is not high enough for the Poisson law to apply. The binomial law gives a more satisfactory explanation.

4. The transformation of contagious data is necessary for populations with mean values of 3 or less. A new square root transformation is presented which gives a more stable variance than Beall's inverse hyperbolic sine transformation for contagious distributions.

5. Both transformations will stabilize the variance and will give a fair approximation to normality as indicated by the β coefficients. Beall's transformation gives a better approximation to normality than the square root transformation.

6. The H. Fairfield Smith empirical law for heterogeneity holds for corn borer infestations although originally used to describe soil heterogeneity. This indicates that there may be a large correlation between soil fertility, larger plants, and more egg masses laid on them.

7. There were some effects in the variances for different sizes of plots which could be due to shape of plot but a multiple regression using a shape factor consisting of the ratio of length of row to number of rows was unsuccessful in describing this effect.

8. A plot used for testing insecticides with power equipment may be as long as 125 feet provided it is four to six rows wide. There was only slight increase in efficiency in using six rows over four.

9. The minimum sample size is twenty plants selected at random within a plot if plot totals are to be analyzed. A chart for determining the sample size is provided.

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APPENDICES

APPENDIX A

Codes for Visual Evaluation of Plant Damage

Visual method for evaluating the amount of plant injury by different levels of European corn borer infestation. Ratings used by the Corn Borer Laboratory at Ankeny, Iowa.

Class 1. No visible leaf injury to a small amount of pin or fine shot-hole type of injury on a few leaves; no visible evidence of stalk invasion.

Class 2. Small amount of shot-hole type lesions on a few leaves and only occasional small lesions on the sheath; occasional indication of stalk invasion.

Class 3. Shot-hole injury common on several leaves of most plants with lesions slightly elongated and occasional midrib and sheath injury; occasional node or internode with evidence of stalk invasion.

Class 4. Several leaves of most plants with shot-hole and elongated lesions; some midrib, leaf collar and sheath injury; most plants with a few node or internode invasions.

Class 5. Several leaves with short elongated lesions; midrib collar and sheath injury on a few leaves; few node or internodes showing evidence of stalk invasion.

Class 6. Several leaves with elongated lesions (about 1 inch); midrib, collar and sheath injury common. Few nodes and internodes showing stalk invasion.

Class 7. Long lesions common on several leaves of most plants; sheath injury and collar girdling common. Stalk invasion evident at several nodes or internodes common.

Class 8. Long lesions common on about 1/2 of the leaves of most plants; severe midrib and sheath damage; about 1/2 of nodes or internodes showing evidence of stalk invasion.

Class 9. Most of leaves with long lesions; severe collar girdling and sheath injury; most of the nodes and internodes showing evidence of stalk invasion.

Suggested methods for making leaf lesion counts.

Count all lesions 1/2 inch in extent on the midrib and sheath. Sometimes it is desirable to count long collar injuries, extending on both sides of the midrib, as 2 lesions. If the counts are made when stalk invasion is sufficiently advanced externally visible burrows can be readily counted.

Visual method for evaluating the amount of plant injury used by the author in classifying part of the plants dissected in experimental area number one.

Light---- Very light evidence of borer activity. Leaves with lesions; no indication of stalk invasion.

Medium--- Evidence of one or two tunnels in stalk.

Heavy---- Evidence of three or more tunnels in stalk.

APPENDIX B

Mathematical Formulae

The negative binomial distribution

If a Poisson parameter λ varies according to a Gamma distribution then the probability of x successes is given by

$$(1) \qquad P_x = \int_0^\infty \frac{c^d}{\Gamma(d)} e^{-c\lambda}\lambda^{d-1} e^{-\lambda} \frac{\lambda^x}{x!} d\lambda$$

$$= \frac{c^d}{\Gamma(d)x!}\int_0^\infty e^{-\lambda(c+1)}\lambda^{d+x-1} d\lambda$$

$$(2) \qquad = \left(\frac{c}{c+1}\right)^d \frac{\Gamma(d+x)}{x!\Gamma(d)} (c+1)^{-x} \qquad , 0 \leqslant x < \infty ,$$

which is the form of the negative binomial given by Kendall (24). To get the form given by most authors let $d = k$ and $c = 1/p$ so that

$$(3) \qquad P_x = q^{-k} \frac{(k+x-1)!}{x!(k-1)!} \left(\frac{p}{q}\right)^x \qquad , 0 \leqslant x < \infty ,$$

where $q = 1+p$.

The moment generating function for the negative binomial is

$$(4) \qquad \phi(t) = \left\{1 - (e^t - 1)p\right\}^{-k} ,$$

and the first 3 moments are:

$$\begin{aligned} \mu_1' &= kp \\ u_2 &= kp(1 + p) \\ \mu_3 &= kp(1 + p)(1 + 2p) \ . \end{aligned} \tag{5}$$

Only the first two moments are needed for fitting, the third may be used to compare the following distributions with this one and for testing the agreement of data to theoretical moments.

Anscombe (2) points out that it is often more convenient to use factorial cumulants in describing discreet distributions so, by letting $e^t = (u + 1)$ in (4) the factorial moment generating function is

$$\phi(u) = \{1 - up\}^{-k} \tag{6}$$

and on taking the natural logarithm of (6)

$$\ln\phi(u) = \psi(u) = -k \ln(1 - up) \tag{7}$$

the required factorial cumulant generating function is found. The i th factorial cumulant is

$$K_{[i]} = (i - 1)!\ kp^i \ . \tag{8}$$

From relation (8) the cumulants and moments are found, as follows:

$$\begin{aligned} \mu_1' &= K_1 = K_{[1]} \\ u_2 &= K_2 = K_{[2]} + K_{[1]} \end{aligned} \tag{9}$$

$$\mu_3 = K_3 = K_{[3]} + 3K_{[2]} + K_{[1]}$$

$$\mu_4 - 3\mu_2^2 = K_4 = K_{[4]} + 6K_{[3]} + 7K_{[2]} + K_{[1]} \ .$$

From the first two moments the value of the parameters are calculated by using the sample estimates of $\mu_1' = \bar{x}$ and $\mu_2 = \hat{\sigma}^2$ both of which are calculated in the usual way. The moment estimates of <u>k</u> and <u>p</u> are,

$$(10) \qquad \hat{k}_m = \bar{x}^2/(s^2 - \bar{x}) \ , \quad \hat{p}_m = \bar{x}/\hat{k}_m \ .$$

If the proportion of zeros is relatively large the parameters of the distribution are fitted by using the proportion of total frequency N to frequency of zeros n_o. The procedure consists of balancing the equation

$$(11) \qquad \hat{k}_f \ln(1 - \bar{x}/\hat{k}_f) = \ln(N/n_o) \ .$$

Once k is estimated p is arrived at as in equation (10).

Anscombe (1) has plotted the large sample efficiencies for the above two estimates of <u>k</u> so that it is a simple procedure, having <u>k</u> and $\bar{x}$, to determine the efficiency. Under certain conditions neither of the above methods results in high efficiency and the method of maximum likelihood, as developed by Fisher and appended to the paper by Bliss (13), is indicated. The procedure consists of computing a score z_1 with trial values of <u>k</u>. The required <u>k</u>$'$ is that for which $z_1 = 0$ in the equation

(12) $$z_i = S\left(\frac{A_x}{k_i' - x}\right) - N \ln(1 + \bar{x}/k_i')$$

where the first trial value is computed from equation (10). A_x is the cumulative frequency of all points greater than x. The variances of $\hat{k}$ for the above three estimates are:

(13) $$\mathrm{Var}(\hat{k}_m) \sim 2d(k + 1)(k + \bar{x})^2 / N\bar{x}^2$$

(14) $$\mathrm{Var}(\hat{k}_f) \sim \frac{(1 - X)^{-k} - 1 - kX}{N\left[-\ln(1 - X) - X\right]^2} \quad \text{where } X = \bar{x}^2/(\hat{k}_f + \bar{x})$$

(15) $$\mathrm{Var}(\hat{k}_{ml}) = (k'_{n-1} - k'_n)/(z_{n-1} - z_n)$$

where $\underline{k}'$ and $\underline{z}$ are the last two values of $\underline{k}'$ and $\underline{z}$ used in estimating $\underline{k}$.

Bliss (13) gives two tests, due to Anscombe, for testing the departure of the data from the negative binomial. Test 1 consists of computing the difference of the third sample moment from its estimated value

(16) $$T = m_3 - \hat{\mu}_3$$

where m_3 is calculated from the sample and $\hat{\mu}_3$ is calculated from the parameters estimated from the first 2 sample moments using the relationship

(17) $$\hat{\mu}_3 = \hat{k}\hat{p}(1 + \hat{p})(1 + 2\hat{p}) \qquad m_3 = s^2(2s^2/\bar{x} - 1)$$

(18) $$\mathrm{Var}(T) \sim s^2\left[1 + p + k + \bar{x}\right]\left[4p^2(3 + 5p) + 6s^2\right] / N \quad .$$

Test 2 consists of computing the difference of the variance from its estimated value.

$$U = s^2 - \bar{x} - \bar{x}^2/\hat{k} \tag{19}$$

$$\mathrm{Var}(u) \sim \frac{2\hat{k}(\hat{k}+1)\hat{p}^2(1+\hat{p})^2}{N}\left[1 - \frac{X^2}{-\ln(1-X)-X}\right] + \hat{p}^4\,\mathrm{Var}(\hat{k}_f) \; . \tag{20}$$

This test is used only when $\underline{k}$ has been estimated from equation (11).

The usual test used in determining the adequacy of the chosen distribution fitting the data is the Chi-square goodness of fit test.

$$\chi^2 = \sum_{x=0}^{\infty}\left[f_x - E(f_x)\right]^2 / E(f_x) = \sum_{x=0}^{\infty}\frac{(f_x)^2}{E(f_x)} - N \tag{21}$$

<u>The Neyman contagious distributions</u>

The Neyman type A arises from a model of randomly distributed egg masses in which the number of egg masses per plot follow a Poisson distribution with mean λ_1 while the number of larvae surviving from each egg mass after a specified time also follow a Poisson distribution with mean λ_1. The probability function is, for $x \geqslant 0$,

$$P_x = \frac{m_2^x}{x!}\sum_{i=0}^{\infty} e^{-m_1}\,\frac{i^x}{i!}\,(m_1 e^{-m_2})^i \tag{22}$$

its moment generating function is

$$(23) \qquad \phi(t) = e^{m_1(e^{m_2(e^t-1)}-1)}$$

which gives the first three moments,

$$(24) \qquad \begin{aligned} \mu_1' &= m_1 m_2 \\ \mu_2 &= m_1 m_2 (1 + m_2) \\ \mu_3 &= m_1 m_2 (1 + 3m_2 + m_2^2) . \end{aligned}$$

The factorial cumulant generating function is

$$(25) \qquad \psi(u) = m_1 (e^{m_2 u} - 1) , \qquad K_{[i]} = m_1 m_2^i .$$

The method of moments may be used to fit the Neyman contagious distributions. It is found that

$$(26) \qquad \hat{m}_1 = \bar{x}^2/(s^2 - \bar{x}) , \qquad \hat{m}_2 = \bar{x}/\hat{m}_1 = (s^2 - \bar{x})/\bar{x} .$$

Shenton (28) has investigated the fitting of this distribution by the method of maximum likelihood and has deduced a series for computing the upper bound for the efficiency of the method of moments. The procedure for computing the maximum likelihood estimate is to calculate a correction term for $\hat{m}_2$ using the probabilities calculated with the moment estimate and then recalculate $\hat{m}_1$. The required formulae are:

$$d\hat{m}_2 = -F(m_2)/F'(m_2) = \text{correction increment}$$

$$F(m_2) = \sum_{x=0}^{\infty} n_x(x+1)\,\frac{P_{x+1}}{P_x} - n\bar{x}$$

(26)

$$F'(m_2) = \frac{1}{m_2}\sum_{0}^{\infty} n_x(x+1)\frac{P_{x+1}}{P_x} - \frac{m_2+1}{m_2^2}\left\{\sum_{0}^{\infty} n_x(x+1)(x+2)\frac{P_{x+2}}{P_x}\right.$$

$$\left. - \sum_{0}^{\infty} n_x(x+1)^2\,\frac{P_{x+1}^2}{P_x^2}\right\} .$$

Once $\hat{m}_2'$ is corrected $\hat{m}_1$ is recalculated as follows, $\hat{m}_1 = \bar{x}/\hat{m}_2$

Bateman (8) has recently investigated the power of index of dispersion as pertaining to the type A distribution. She shows that whereas the index of dispersion for the Poisson is distributed as χ^2 with n-1 degrees of freedom, for the type A it is distributed as $(1+m_2)\chi^2$ with n-1 degrees of freedom. The index of dispersion is

$$d = \frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{\bar{x}} . \tag{27}$$

The $(1+m_2)\chi^2$ approximation to the distribution of d may be used for:

1. Determining the size of sample required in order to have a given chance <u>a</u> of detecting a departure from randomness.

2. Testing the null hypothesis that samples have come from a type A with a given m_2.

(28) $\quad P\{\chi^2 > d/(1 + m_2)\}$.

3. Testing the hypothesis that $m_2 = 0$ using a significance level a.

According to Anscombe (2) the more complex Neyman distributions can be regarded as the limit of the sum of a large number of random variables following independent type A distributions with the value of m_2 distributed in a range $(0, m_2)$.

The moment generating function for the type B is,

$$\phi(t) = e^{-m_1\left\{\frac{e^{m_2(e^t-1)}-1}{m_2(e^t-1)} - 1\right\}} \tag{29}$$

while that for type C is,

$$\phi(t) = e^{-m_1\left\{\frac{e^{m_2(e^t-1)}-1-m_2(e^t-1)}{\frac{1}{2}\left[m_2(e^t-1)\right]^2} - 1\right\}} \tag{30}$$

Little work has been done with the above two distributions. Neyman (25) has given recurrent formulae for fitting them, and Beall (10) has fitted all three Types to corn borer data, concluding that Type C generally gave the best fit when applied to survival data.

The estimation of the parameters is not difficult since they may be derived from the parameters for the type A. They are related in the following way:

Type A	Type B	Type C
m_1	$3/4\ m_1 = m_1'$	$2/3\ m_1 = m_1''$
m_2	$2/3\ m_2 = m_2'$	$1/2\ m_2 = m_2''$.

The recurrent formulae are:

Type A

$$(31)\quad \begin{cases} P_0 = e^{-m_1(1-e^{-m_2})} \\ P_{x+1} = \dfrac{m_1 m_2 e^{-m_2}}{x+1} \displaystyle\sum_{k=0}^{x} \dfrac{m_2^k}{k!} P_{x-k} \end{cases} ,$$

Type B

$$(32)\quad \begin{cases} P_0 = e^{-\frac{m_1'}{m_2'}(e^{-m_2'}-1+m_2')} \\ P_{x+1} = \dfrac{m_1'}{(x+1)m_2'} \displaystyle\sum_{k=0}^{x} (k+1)\left(1-e^{-m_2'}\sum_{j=0}^{k+1}\dfrac{m_2'^{\,j}}{j!}\right) P_{x-k} \end{cases} ,$$

Type C

$$(33)\quad \begin{cases} P_0 = e^{\frac{2m_1''}{[m_2'']^2}\left(e^{-m_2''}-1-\frac{[m_2'']^2}{2}+m_2''\right)} \\ P_{x+1} = \dfrac{2m_1'' e^{-m_2''}}{(x+1)[m_2'']^2} \displaystyle\sum_{k=0}^{x} (k+1)\left(m_2''\left[e^{m_2''}-\sum_{j=0}^{k}\dfrac{m_2''^{\,j}}{j!}\right] \right. \end{cases}$$

$$\left. -(k+2)\left[e^{m_2''}-\sum_{j=0}^{k+1}\frac{m_2''^{\,j}}{j!}\right]\right)P_{x-k} .$$

The above distributions may have one or more modes. More than one mode will appear when m_2 is larger than m_1.

Anscombe (2) gives an example where $m_1 = 2$ and $m_2 = 10$ which has three well defined modes. The value of m_2 is a reflection of the heterogeneity present in the population.

The Thomas distribution

This contagious distribution is based on a model of randomly distributed plant colonies in which the plants in each colony in excess of the central plant follow the Poisson law.

The successive probabilities are given by

$$(34) \qquad \begin{cases} P_o = e^{-m} \\ P_x = \sum_{r=1}^{x} m^r e^{-m} (r\lambda)^{x-r} e^{-r\lambda} / r!(x-r)! \qquad x = 1,2,3,\cdots . \end{cases}$$

The moment generating function is

$$(35) \qquad \phi(t) = e^{m\left\{e^t e^{\lambda(e^t-1)} - 1\right\}}$$

and the factorial cumulant generating function is

$$(36) \qquad \psi(u) = m\left\{(1+u)e^{\lambda u} - 1\right\}$$

so that

$$(37) \qquad K_{[i]} = im\lambda^{(i-1)} + m\lambda^i$$

which gives the first three moments

$$(38) \qquad \begin{aligned} \mu_1' &= m(1+\lambda) \\ \mu_2 &= m(1 + 3\lambda + \lambda^2) \\ \mu_3 &= m(1 + 7\lambda + 6\lambda^2 + \lambda^3) \,. \end{aligned}$$

In order to see the relationship of this distribution to those previously discussed let $\lambda = (m_2 - 1)$ where $m_2 = p$ and $m = m_1 = k$ as in the negative binomial and the Neyman type A; then

$$(39) \qquad \mu_1' = m_1 m_2 \quad \text{and} \quad \mu_2 = m_1 m_2(1 + m_2 - 1/m_2)$$

which may be compared with equations (5) and (24). For small values of m_2 the variance of the Thomas distribution will be less than that of either the negative binomial or the Neyman type A. For large values of m_2 the variances of the three distributions will be approximately equal.

The parameters of the distribution may be estimated by the method of moments, or by a method of maximum likelihood using the frequencies of zeros and ones. The method of moments gives an estimate of from the following relation

$$(40) \qquad \hat{\lambda} = -\frac{(3-\frac{s^2}{\bar{x}})}{2} \pm \sqrt{\frac{(3-\frac{s^2}{\bar{x}})^2}{4} - (1-\frac{s^2}{\bar{x}})}$$

where the positive solution is used. The primary parameter is then estimated from

$$(41) \qquad \hat{m} = \bar{x}/(1+\hat{\lambda}) \,.$$

To get a maximum likelihood estimate the simultaneous solution of

(42) $$e^{-m} = n_o/N \quad , \; me^{-\lambda} = n\ /n_o$$

is required.

The Polya-Eggenberger distributions

The Polya-Aeppli distribution is based on a model in which the individuals in randomly distributed colonies follow a geometric distribution.

The frequency function is

(43) $$\begin{cases} P_o = e^{-m_1} \\ P_x = e^{-m_1}\tau^x \sum_{j=1}^{x} \binom{x-1}{j-1} \frac{1}{j!} \left(\frac{m_1(1-\tau)}{\tau}\right)^j \quad , x \geqslant 1 \ . \end{cases}$$

The moment generating function is

(44) $$\phi\,(t) = e^{\frac{m_1(e^t-1)}{1-\tau-\tau(e^t-1)}}$$

and the factorial cumulant generating function is

(45) $$\psi\,(u) = \frac{m_1 u}{1-\tau-\tau u}$$

so that the factorial cumulants are:

(46) $$K_{[i]} = \frac{i!m_1\tau^{(i-1)}}{(1-\tau)^i} \quad .$$

The first three moments are:

$$\mu_1' = \frac{m_1}{(1-\tau)}$$

(47) $$\mu_2 = \frac{m_1}{(1-\tau)}\left(1 + \frac{2\tau}{1-\tau}\right)$$

$$\mu_3 = \frac{m_1}{(1-\tau)}\left(1 + \frac{2\tau}{1-\tau} \quad \frac{6\tau^2}{(1-\tau)^2}\right) \quad .$$

The parameters are estimated by the method of moments from the following relations:

$$\hat{m}_1 = \frac{2\bar{x}^2}{s^2 + \bar{x}} \quad , \qquad \hat{\tau} = \frac{(s^2 - \bar{x})}{(s^2 + \bar{x})} \quad .$$

For further information on the fitting of this distribution see Evans (18).

The Poisson binomial contagious distribution

If an insect lays egg masses over a field at random and the number of egg masses per unit area follow a Poisson distribution while the survivors of the $\underline{n}$ eggs per egg mass follow a binomial distribution we have a contagious distribution related to the Neyman type A which is here designated as the Poisson binomial contagious distribution.

The moment generating function follows directly from the moment generating function for the generalized Poisson as developed by Satterthwaite (27) and given by Feller (19).

The moment generating function is:

(48) $$\phi(t) = \exp\left\{a\left[(pe^{t}+q)^{n} - 1\right]\right\}$$

which gives the factorial moment generating function on letting $e^{t} = u + 1$, hence

(49) $$\phi(u) = \exp\left\{a\left[(p(u+1) + q)^{n} - 1\right]\right\}$$

and the factorial cumulant generating function is

(50) $$\psi(u) = a\left[(p(u+1) + q)^{n} - 1\right]$$

which gives the i th factorial cumulant

(51) $$K_{[i]} = an^{(i)}\, p^{i} \text{ where } n^{(i)} = (n-0)(n-1)(n-2)\cdots(n-i+1)$$

so that the moments are:

(52) $$\begin{aligned} \mu_1' &= nap \\ \mu_2 &= nap(1+(n-1)p) \\ \mu_3 &= nap(1+3(n-1)p + (n-1)(n-2)p^2)\ . \end{aligned}$$

The parameters of the distribution may be estimated by the method of moments using the following relations:

(53) $$\begin{aligned} \hat{a} &= (n-1)\, \bar{x}^2 / n(\hat{\sigma}^2 - \bar{x}) \\ \hat{p} &= (\hat{\sigma}^2 - \bar{x}) / \bar{x}(n-1)\ . \end{aligned}$$

The appropriate value of <u>n</u> may be determined once for any given insect and will in general be a low value, $2 \leqslant n \leqslant 4$. For the corn borer the appropriate value of <u>n</u> is 2, while for <u>Carex</u> <u>flacca</u> Schreib. Skellam determined <u>n</u> to be 3.

A preliminary estimate of n may be made using the frequencies at 1 and 2, by minimizing

$$2R(n-1-y) - (n-1)y = (n-1-y)^n/(n-1)^{n-1} \tag{54}$$

where $R = f_2/f_1$ and $y = (\hat{\sigma}^2 - \bar{x})/\bar{x}$.

From equations (53) it is easy to see that as <u>n</u> increases <u>a</u> will approach m_1, the main parameter of the Neyman type A distribution, while p will approach 0. The Poisson binomial distribution will then be identical to the Neyman type A. As n approaches 1 all the frequency is concentrated at the point $x = 0$. Whenever the moment estimates of the Neyman type A parameters give an expected value at $x = 0$ which is less than the observed value it is expected that the Poisson binomial will give a better fit than the Neyman type A.

The distribution is fitted by means of the recurrent expression

$$\begin{cases} P_0 = e^{-a(1-q^n)} \\ P_x = \dfrac{\bar{x}}{x!} \displaystyle\sum_{i=0}^{x-1} \binom{x-1}{i} \frac{(n-1)!}{(n-x+i)!} p^{x-i-1} q^{n-x+i} \, i! P_i \end{cases} \tag{55}$$

It has been found expedient to use the following relations for all calculations:

$$(56)\qquad \begin{cases} F_o = e^{-a(1-q^n)} \\ F_x = \bar{x} \sum_{i=0}^{x-1} \binom{x-1}{i} \frac{(n-1)!}{(n-x+i)!} p^{x-i-1} q^{n-x+i} F_i \end{cases}$$

and getting the probabilities from

$$(57)\qquad P_x = F_x \,/\, x! \,.$$

APPENDIX C

Plot Data

Table 13.

Number of plants, cavities, and borers by instar, per plot. All plants dissected in experimental area number 1; one plant sampled from each hill in experimental areas 2 through 4.

Experimental Area Number One.

Plot No.	Plants	C*	P*	5*	4*	3*	2*	Total Borers
1	10	31	3	12	5	1		21
2	7	37	1	2	12	9		24
3	9	34	4	18	4	2		28
4	10	29	10	22	3	1		36
5	11	35	4	5	4	3		16
6	9	41	3	14				17
7	11	54	11	19	5	2		36
8	10	42	8	19	4			31
9	11	38	9	14				23
10	9	20	2	4	5	4		15
11	10	32	7	13	3	2		25
12	11	43	7	12	7	2		28
13	11	40	6	21	2			28
14	11	59	8	31	3			42
15	11	44	3	21	1	4		29
16	9	25	1	8	3	1		13
17	10	41	5	18	2	3		28
18	11	47	9	12	8			29
19	9	38	7	13	5	1		26
20	7	18	2	5	4	1		12
21	10	25	3	8	4	2		17
22	9	27	3	10	3			16
23	11	17	3	6				9
24	11	34	2	11	3	1		17
25	9	25	4	13	1			18
26	9	46	9	16	6	3		34
27	9	26	2	5	2			9
28	12	40	6	18		1		25
29	11	24	1	14	1			16
30	10	38	9	14	4			27

* C = number of cavities
P = pupae
5 = fifth instar larvae
4 = fourth instar larvae
3 = third instar larvae
2 = second instar larvae

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
31	10	44	3	16	7		1	27
32	9	38	5	13	2	1		21
33	8	38	9	13	4	1		27
34	10	48	2	27	8	1		38
35	10	39	3	17	2	1	1	24
36	7	29	3	6	3			12
37	7	20	4	9				13
38	11	51	5	23	3			31
39	9	14		3	3			6
40	10	40	5	17	5	4		31
41	8	28	2	12				14
42	9	14	1	9				10
43	10	30	4	8	2	2		16
44	8	18	1	8	4	1		14
45	7	15	2	8	2			12
46	9	29	2	13	2			17
47	9	27	6	7	2	2		17
48	8	44	10	10	14	4		38
49	8	33	4	17	1			22
50	6	22	8	6	1			15
51	10	34	12	13	4	4		33
52	9	44	6	16	6	3		31
53	10	23	9	9		2		20
54	12	36	13	24	2			39
55	12	39		11	9	10		31
56	10	44	1	16	3	3		23
57	12	26	5	9	4	3		21
58	8	40	3	13	5	1		22
59	11	29	3	16	4	3		26
60	10	37	5	19	4	2		30
61	10	40	5	12	5	4		26
62	11	51	5	16	4			25
63	10	34	4	8	3			15
64	9	28	7	9	2			18
65	10	42	2	20	3	2		27
66	11	53	5	17	6			28
67	7	23	4	12	1	1		18
68	10	22	2	4	4	3		13
69	10	24	1	13		1		15
70	10	33	3	13	2	1		19
71	9	35	13	12	3	2		30
72	9	34	8	17	4	2		31
73	11	34	1	8	7	5		21
74	10	29	5	5	3			13
75	9	26	6	18	3	3		30
76	10	40	17	20	9			46

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
77	10	27	1	10	5			16
78	12	46	4	24	1			29
79	12	58	5	23	7	7		42
80	10	33	1	18	2	3		24
81	9	36	4	9	4	4		21
82	11	41	5	15	3	3		26
83	11	35	3	10	4	5		22
84	11	33	7	19	6	1		33
85	11	43	3	15	3	1		22
86	11	27	8	8	1	1		18
87	10	28	8	5	2	2		17
88	11	60	16	25	7	2		50
89	12	45	9	15	1			25
90	11	33	9	7	3	5		24
91	10	31	3	10	2			15
92	10	26	7	12				19
93	12	32	3	13	4	1		21
94	12	38	4	17	1	6		28
95	11	34	6	10	6	1		23
96	9	29	3	16		1		20
97	10	28	3	10	2	5		19
98	10	34	4	11	5	4		24
99	8	25	2	5	6	1		14
100	11	44	5	16	4	1		26
101	10	28	1	13	5	3		22
102	9	39	8	18	1			27
103	10	39	10	14	2			26
104	9	34	2	12	2	2		18
105	10	41	5	21	3			29
106	11	44	8	19	2	2		30
107	10	33	6	15	3	1		25
108	9	42	1	22	5	1		29
109	9	24	2	11	1	3		17
110	8	28	3	14	3	2		22
111	11	39	5	12	6	1		24
112	9	43	6	18	2	2		28
113	10	36	3	16	1			20
114	11	20	2	7	1			10
115	11	36	3	13				16
116	11	25	2	8	3			13
117	10	35	9	5	2			16
118	7	13	2	5	2			9
119	11	28	7	7	3	2		19
120	11	45	1	22	5			28
121	11	32	3	13	2	1		19
122	11	37	5	16	2	4		27

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
123	7	29	6	13	1			20
124	10	40	9	16	6	1		32
125	11	44	4	17	5	3		29
126	10	36	11	17	4	1		33
127	8	30	1	9	1			11
128	10	36	2	12	8	3		25
129	11	50	5	26	1	1		33
130	7	30	1	13	3	3		20
131	12	56	11	15	9	4		39
132	10	35	9	19		3		31
133	12	48	4	18	3	2		27
134	11	28	2	14	3	2		21
135	8	34	7	14	1			22
136	11	31	13	15	4	2		34
137	11	31	6	10	7			23
138	11	55	14	24	4			42
139	11	59	5	34	3			42
140	11	46	6	21	2	1		30
141	11	34	8	12	3	2		25
142	12	49	5	17	3	1		26
143	12	52	16	11	8	1		36
144	10	38	10	15	4			29
145	9	35	4	13				17
146	11	45	10	10	6	3		29
147	10	54	6	28	7			41
148	8	29	3	13	2	5		23
149	11	58	6	34	15	3	1	59
150	11	46	4	24	8	4		40
151	10	42	5	20	3			28
152	12	36	3	13	5	4		25
153	10	41	19	22	3			44
154	11	35	17	15	1	3		36
155	11	32	3	12	7			22
156	11	44	10	22	6	4		42
157	10	35	16	3	2	8		29
158	11	42	3	15	3	2		23
159	9	37	4	19	2			25
160	11	61	10	20	7	6		43
161	11	38	18	15	3	1		37
162	11	43	6	21	6	4		37
163	8	38	15	16	2	1		34
164	9	31	6	18				24
165	7	15	1	5	1			7
166	8	39	5	19	5	1		30
167	12	52	7	14	6	7		33
168	9	32		14	6	2		22

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
169	10	38	5	17	8	2		31
170	8	30	8	11				21
171	9	37	3	17	6	1	1	28
172	9	41	8	17	5	2		32
173	8	30	1	10	2	2		15
174	11	36	11	13	1	2		27
175	11	60	5	31	9	7		52
176	9	39	5	22	5	2		34
177	10	27	7	16	2	1		26
178	11	42	1	23	4			28
179	11	42	10	15	3	1		29
180	11	41	1	20	9	2		32
181	8	33	2	11	6	4		23
182	8	19	1	3	4	3		11
183	9	21	1	7	3			11
184	10	35	4	11	4	7		26
185	10	32	12	25		3		40
186	11	28	1	11	2	3		17
187	9	35	2	11	3			16
188	10	36	16	13	4			33
189	8	30	6	11	2	5		24
190	11	32	13	18	3	2		36
191	8	28	2	13				15
192	11	41	8	9	2			19
193	11	38	4	19	4			27
194	9	26	12	13		2		27
195	12	39	4	11	9	6		30
196	9	33	4	16	2	4		26
197	11	55	15	9	19			43
198	8	24	3	4	3	2		12
199	10	28	2	10	5			17
200	10	30	8	17		1		26
201	11	26	3	12	6	5		26
202	9	32	3	12	4	1		20
203	12	49	8	18	7	7		40
204	11	58	3	22	7	5		37
205	8	35	1	17	5	1		24
206	10	41	13	17	5	2		37
207	8	35	11	18				29
208	11	49	5	16	7	6		34
209	9	31	2	13	6	4		25
210	12	43	8	16	5	3		32
211	9	37	2	16	8	5		31
212	11	40	7	12	7	1		27
213	10	44	7	19	9	1		36
214	11	43	3	16	4	5		28

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
215	10	47	14	21				35
216	11	33	9	8	3			20
217	9	31	2	9	9	3		23
218	12	46	15	24	3	2		44
219	12	48	7	21	6	2		36
220	9	60	11	20	12	5		48
221	7	34	6	13	4	5		28
222	11	44	6	19	10	2		37
223	12	46	3	24	4	5		36
224	12	39	13	22		3		38
225	12	42	12	19	6	1		38
226	11	54	12	24	7	1		44
227	10	34	5	13	4			22
228	11	53	16	5	17	2		40
229	10	37	4	14	4	4		26
230	9	33	3	18				21
231	10	37	2	17	3	1		23
232	11	34	4	13	3			20
233	10	41	4	11	4	7		26
234	9	49	7	14	9	8		38
235	12	36	4	13	8	2		27
236	7	17	3	8	1			12
237	8	22	1	13	2			16
238	10	33	6	13	2	3		24
239	8	22	2	7	7			16
240	12	34	2	12	4	7		25
241	9	29	3	7	3	3		16
242	11	32	2	18	2			22
243	8	22	4	12				16
244	9	32	2	14	1	2		19
245	10	19	2	8	1	2		13
246	11	50	6	22	7	3		38
247	10	42	12	15	4	2	1	34
248	10	38	7	16	4	1		28
249	10	36	8	14	3	3		28
250	11	29	9	3	4			16
251	12	39	15	21	8	4		48
252	9	25	6	14		1		21
253	9	24	1	13	7	1		22
254	8	31	7	15				22
255	11	29	8	15	2			25
256	9	18	1	6	3	1		11
257	12	24	8	7	2	1		18
258	9	36	7	18	3	1		29
259	8	26		13	4	1		18
260	9	30	7	17	1			25

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
261	7	19	2	3				5
262	11	44	9	14	1	1		25
263	12	30	4	11	1			16
264	10	29	8	7	3			18
265	11	41	3	21	7	2		33
266	8	33	3	17	7	2		29
267	9	27	8	15	4			27
268	6	12	3	5		1		9
269	6	14	1	10	2	3		16
270	9	18	10	8	1	1		20
271	11	46	9	18	2			29
272	10	41	10	19	4	2		35
273	10	40	6	19	4	2		31
274	11	52	4	13	7	5		29
275	11	43	9	21	6			36
276	10	18	2	8	1	1		12
277	7	25	8	8	3	3		22
278	11	31	14	13	2	3		32
279	10	44	4	21	3	5	2	35
280	9	51	9	28	1			38
281	11	42	4	21	9	3		37
282	12	37	7	24	2	1		34
283	10	38	8	15	5	1		29
284	10	37	6	12	1			19
285	10	35	2	14	8	1		25
286	9	31	4	18	2			24
287	10	53	11	11	10	3		35
288	12	49	23	23	4	6		56
289	8	24	6	5	4	3		18
290	9	26	11	6	1	2		20
291	10	48	3	17	9	4		33
292	8	35	6	15	3			24
293	9	32	3	18	1	1		23
294	9	30	8	10	2	3		23
295	11	35	9	8	8	1		26
296	10	21	8	3	2			13
297	9	55	3	33	1			37
298	9	35	7	9	5	3		24
299	12	51	3	22	9	5		39
300	11	39	7	20	4	1		32
301	9	27	3	14	5	4		26
302	7	23	3	15	1			19
303	11	31	8	9	2	1		20
304	9	28	4	14	1	1		20
305	9	25		7		2		9
306	9	31	5	15	5	1		26

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
307	8	22	4	6	1			11
308	10	33	2	16	4	3		25
309	10	51	5	26	4			35
310	12	50	9	19	6			34
311	12	39	4	17	8			29
312	10	33	5	11		1		17
313	11	30	2	15	6	2		25
314	9	35	9	13	5			27
315	7	23	2	11				13
316	12	44	11	19	3	1		34
317	8	21	8	8	2			18
318	11	30	8	12	9	2		31
319	10	35	5	12	6	3		27
320	10	38	4	25				29
321	10	35	7	10		2		19
322	10	37	11	17	2			30
323	8	30	8	13				21
324	9	32	2	11	1	3		17

Experimental Area Number Two

Plot No.	Plants	C	P	5	4	3	2	Total Borers
1	11	2	1	1				2
2	11	4		2		3		5
3	10							
4	11	3			2	1		3
5	10	9	1	4	2	2		9
6	11	7		4	1			5
7	11	11	1	2	4			7
8	11	3			2		1	3
9	10	10	2		2	1		5
10	12	11	1	3		1		5
11	10	4	1	2				3
12	10	7	1	3	1	1		6
13	12	4		1				1
14	8	2						
15	11	12		4	1			5
16	13	9	1	4				5
17	11	10	4	1				5
18	10	5		1	1			2
19	12	8						
20	12	11	1	2	2	1	1	7
21	12	11		2	1	1		4
22	12	8		2	1	1	1	5

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
23	11	6		4		1		5
24	12	9	2		2			4
25	11	6		1				1
26	12	4	1	2	3	1		7
27	12	9		1	3	1		5
28	11	13	2	1	2	2		7
29	11	13		2	2	2		6
30	12	9		1	2	1		4
31	11	9	3	3	1			7
32	12	13		2	2	1		5
33	12	10		5	2			7
34	9	2		1	2	3		6
35	11	15		6	2			8
36	10	12		3				3
37	13	4						
38	11	8	2	1	1			4
39	11	4	1	2	2			5
40	11	13	1	4	6	1		12
41	13	3	1	2	1			4
42	12	8		3	2			5
43	11	12	1	4	2	2		9
44	10	6	1	1				2
45	11	6		3			1	4
46	11	10	1	2				3
47	13	12		4	1	2	1	8
48	10	8	1	2	1			4
49	11	8		2	2	1		5
50	12	5		1	2	2		5
51	10	9	3	2	1			6
52	11	10	2	7	3			12
53	10	8	1	2	1			4
54	13	11		3	2			5
55	10	13	1	6	3	1		11
56	12	15		5	2	3		10
57	9	12		4	1			5
58	13	5		2				2
59	14	7		1		1		2
60	12	5						
51	11	10	1	1				2
62	11	8	2	3		1		6
63	11	7	2	2				4
64	10	7		2				2
65	12	7	1	2	1	1	1	6
66	11	6		2	1			3
67	12	8	1	2	2			5
68	10	11	1	2		1		4

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
69	9	5	1					1
70	11	13		2				2
71	11	12		2	1	2	1	6
72	11	6						
73	12	18		6	1	4		11
74	11	13		8				8
75	9	15	1	9	2		1	13
76	10	8		2	1			3
77	11	6		2	1	2		5
78	11	8		5				5
79	10	13	1	3	1	3		8
80	12	13	1	4	1	1	1	8
81	8	10	1	3				4
82	9	9		9	1		2	12
83	9	7		4	2			6
84	11	9	1		4	3	1	9
85	11	9		3				3
86	11	11		5		2		7
87	11	10				3		3
88	10	5			1			1
89	7	11	1	3	3	2		9
90	9	9		2	2	1		5
91	9	6	1	1	3			5
92	10	6	1	1	1	1	1	5
93	9	6		1	1			2
94	10	9	1	4		1		6
95	11	6	1		3			4
96	11	3	1			1		2
97	10	10	1	2		2		5
98	12	7			1	1		2
99	10	9	2		2	3		7
100	10	10		1	1	2		4
101	12	13		6	1			7
102	11	5		1				1
103	12	4		2	1	1		4
104	11	12		4				4
105	12	6		1	1		1	3
106	11	4	1			2		3
107	11	7				1		1
108	10	9	1	1	2	1		5
109	10	8		3	1	1		5
110	11	8		4	1	2		7
111	9	11		2	3	1		6
112	11	6		1	1	2	1	5
113	11	8	1	4		1		6
114	13	7		2	2		1	5

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
115	9	15	2	7				9
116	11	6		1		1		2
117	12	5	1	1				2
118	10	12	3	4		1		8
119	8	4	1	1	1	1	1	5
120	10	10	2	2				4
121	11	2		2				2
122	9	5		1	1	1		3
123	9	4		1				1
124	12	5		1	4			5
125	12	10		4	1	1	1	7
126	11	8		3	1	1	2	7
127	12	11	1	3	3		1	8
128	11	11	3	2	3	2		10
129	12	10		4				4
130	11	6	1	1		2		4
131	11	9	2	1	1			4
132	8	2						
133	11	9	2	3				5
134	10	10	3	3	1	2		9
135	10	12	1	2	1			4
136	11	9	2	1				3
137	8	8		3	1	2		6
138	10	7		2		1		3
139	10	6	2	2	2			6
140	9	5	1	1	1	2		5
141	10	5			1			1
142	13	8		3	1			4
143	12	8	1	3	2			6
144	11	8	3				1	4
145	9	11	2	6				8
146	10	17		6	2	1		9
147	9	12	2	4	1			7
148	12	8		1		1		2
149	11	10	1	3	1	1	3	9
150	10	11		5	2	2		9
151	12	13	2	6	2			10
152	9	18	1	4	2	2	5	14
153	9	12	2	2	4	2		10
154	11	11		2	3			5
155	11	6		3				3
156	8	10		3				3
157	8	7		3		1	1	5
158	12	7	4	1	2			7
159	9	17	2	2	3	1		8
160	8	14		4	3	5	1	13

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
161	11	8			1	1		2
162	10	17		5	4	1		10
163	7	19	2	12	2	1		17
164	13	9		4	3	1	1	9
165	10	16		4		2		6
166	11	13	2	2	1			5
167	9	15	1	7	1	2		11
168	11	13						
169	10	13	1	5	1		2	9
170	11	11	2	2	1			5
171	11	14	2	9	2	2	1	16
172	12	16		5	2			7
173	12	6		1				1
174	11	4	1	1	1			3
175	12	9		4	1	2	1	8
176	12	6	1	3		1		5
177	12	16	1	1	1	3		6
178	10	8	1	1		1		3
179	11	10		2	1	1		4
180	9	16	1	7	3		1	12
181	11	6		1	3	4		8
182	10	11		7				7
183	9	8		4		1		5
184	11	10	1	2	2			5
185	9	6		2	1			3
186	11	7		5	4	2		11
187	12	6		2				2
188	12	17	1	1	1	2		5
189	13	17		7	4	4		15
190	12	13	2	5	6	1	2	16
191	11	7	1		1	1		3
192	12	16		2	2	2	1	7
193	12	8		1			1	2
194	13	8			2			2
195	12	7		4	2	1		7
196	11	8	2	1	3			6
197	11	5		1	2			3
198	10	9	1	1	4			6
199	16	6		1	2	1		4
200	13	11		5				5
201	12	4		1	1			2
202	11	10		6				6
203	12	7	1	4				5
204	14	12	2	1	3	1		7
205	15	9		1		1		2
206	9	20	1	1	5	1		8

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
207	15	6				1	1	2
208	11	8		5	2			7
209	12	8	2			2		4
210	13	8	1	2				3
211	12	10	1	2		3		6
212	10	9		2		1		3
213	13	10	3	1		2		6
214	13	13	2	4	2	1		9
215	13	7			1			1
216	12	4	1		1			2
217	16	9		7		1	1	9
218	13	7		5	2	2		9
219	15	10	1	2	1	1		5
220	12	9		2	3			5
221	10	11	2	5	1	1		9
222	13	13		4	1	1		6
223	13	7		1	1			2
224	13	6		1	1			2
225	14	4		1	1	1		3
226	10	4		1				1
227	10	18	1	5	2	2		10
228	11	18	2	6	5			13
229	11	8		1				1
230	15	5		1	1			2
231	12	8		1		1		2
232	13	9		1				1
233	9	2			1	1		2
234	12	7		3		2	1	6
235	11	9		4				4
236	13	7		2	2	1		5
237	12	9	1	3	2		1	7
238	13	10		5	4	2	3	14
239	14	8		5	1			6
240	14	7		5	1	2		8
241	12	11		3	2			5
242	14	7		3			1	4
243	13	4			4			4
244	11	5						
245	12	12		6	2	3	2	13
246	10	6		2			1	3
247	13	9		3	3	1		7
248	13	10		4				4
249	9	7	1	2		2		5
250	10	10		6	1			7
251	13	7		1		1		2
252	11	6		3				3

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
253	15	8		4	1		1	6
254	12	6		3	1			4
255	11	8		2		4	2	8
256	13	6	1	1				2
257	11	6	1		1			2
258	9	5				2		2
259	14	11	1	3	3	2		9
260	14	1		1	1	1	1	4
261	13	5			1	1		2
262	12	11	1	5	1	1		8
263	12	11	1	3		1	1	6
264	11	6	1		1			2
265	14	4		1				1
266	13	8		4	1	2	1	8
267	15	4	1	1	1	1		4
268	10	17	1	4	2	2		9
269	11	3				2	1	3
270	12	10		4	1	1		6
271	14	6		4	2			6
272	14	13	1	3	1			5
273	13	6		1	1	4		6
274	11	3	1	1		3		5
275	15	2		1		3		4
276	15	9		2	3	2		7
277	12	14		4	1	1	2	8
278	15	12	1	3	1			5
279	16	6	1	1	1	1		4
280	10	5		1		2		3
281	13	3					1	1
282	13	6			1			1
283	15	9		5	2	1		8
284	13	12		5	1			6
285	13	8	1	1	1	3		6
286	13	14		6	2	1		9
287	13	13	2	4	3			9
288	10	11		5				5
289	12	11		4				4
290	14	3	1	2				3
291	10	6		3		1		4
292	9	7		1				1
293	15	7	2	3				5
294	12	7	1	2		1		4
295	11	12		2	1	3		6
296	14	8		2	1	1	1	5
297	11	8		2				2
298	12	6	1	1	2			4

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
299	13	5		3	3	1	1	8
200	14	4		2	1	1		4
201	12	11	1	3		2	1	7
302	10	9		3				3
303	12	15	1	4				5
304	13	7		5	1			6
305	11	8	1	2				3
306	12	7		1	1	2		4
307	13	7		5				5
308	13	6			1	1		2
309	15	10		4	2			6
310	13	8					2	2
311	13	15		15	4	3	2	24
312	14	6		3				3
313	12	16	1	1	1	2	1	6
314	12	3	1	1				2
315	14	6				1		1
316	14	10	2	1	2	1		6
317	12	8	1	1		1		3
318	11	8	1	1	3			5
319	11	9		7		3		10
320	13	7	1	2	1	1	2	7
321	11	11	1	2	1			4
322	13	1						
323	11	5		1			1	2
324	12	6		1	1	2		4

Experimental Area Number Three

Plot No.	Plants	C	P	5	4	3	2	Total Borers
1	12	5		1				1
2	9	3						
3	11	3						
4	9	13	1	2				3
5	12	11		1				1
6	10	1						
7	12							
8	10	6	1	1	1			3
9	7	5		3				3
10	10	6		3	2			5
11	12	4		1		1		2
12	11	3	1					1
13	12	3	1	1				2
14	10							
15	11	4						

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
16	12	2			1			1
17	10							
18	12							
19	10	4						
20	9	6	1					1
21	8	10	3					3
22	12	5		2				2
23	11	4						
24	11	7		1				1
25	11	8						
26	9	4	1	2				3
27	11	6	1	1				2
28	10	3						
29	11	4		2		1		3
30	12	5						
31	12	7		1				1
32	9	7	1	3	2			6
33	12	3		1				1
34	11	3						
35	10	4	1					1
36	11	5						
37	9	8	1	1	1	1		4
38	10	2	1					1
39	12	12		1				1
40	12	4		2				2
41	12	9	1		1			2
42	11	11		3				3
43	11	5	2			1		3
44	12	8		2				2
45	9	4			2			2
46	12	3			1			1
47	11	4		1	1			2
48	12							
49	11	4	1	1				2
50	12							
51	11	6	1		1			2
52	12	9						
53	12	9	1	2	1			4
54	11	3		2				2
55	9	2		1				1
56	12	12		6	1			7
57	9	11	1	2				3
58	11	1		1				1
59	12	5	2	1				3
60	11	9				1		1
61	11	8	3	1				4

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
62	12	4						
63	11	4	1					1
64	10							
65	11	5		3				3
66	11	1						
67	9	4		3				3
68	10							
69	12							
70	11	1						
71	10	4		1				1
72	10	7		3				3
73	12	5	1	2				3
74	11	6		1				1
75	7	5						
76	11	3				1		1
77	10	2						
78	9	3		1				1
79	10	9		2		1		3
80	9	6	1					1
81	12	7	1	4	1	1		7
82	7	12		1		2		3
83	11	5			1			1
84	7	4			1	1		2
85	11	1						
86	12	1		1				1
87	12							
88	8	2			1			1
89	8	2		1	1			2
90	6	3	1	1				2
91	11	6	1	1				2
92	10	6		5				5
93	11	7	1	4				5
94	9	5		1				1
95	11	5	1	3				4
96	11	5		1				1
97	11	8		6				6
98	7	4		1				1
99	9	2	1					1
100	10	3						
101	10	3						
102	12	5	1	2				3
103	11	13		1		2		3
104	10	1		1				1
105	10	12		1	1	1		3
106	9	7						
107	9	4	1	1				2

Table 13 (Continued)

Plot No.	Plants	C	P	5	4	3	2	Total Borers
108	11	7		1	1	1		3
109	11	2	1	1				2
110	11	4		1	1			2
111	8	6		2				2
112	11	4	1					1
113	11	6	1	1				2
114	10							
115	11	4						
116	9	5		1	1		1	3
117	12	3						
118	7	3	1					1
119	10	8		1				1
120	10	2		1				1
121	12	2						
122	12	2		1				1
123	8	3						
124	10	2		1				1
125	9	2						
126	10	4		2				2
127	12	3						
128	11		1					1
129	11	3						
130	12	6		2		1		3
131	9	1		1			1	2
132	11	7		4				4
133	10	8		1				1
134	9	7	2	1				3
135	11	2		1				1
136	11	6	2	1				3
137	12	5		4				4
138	11	7		1	2	2		5
139	11	3		3				3
140	11	7			1			1
141	9	5	1					1
142	11	3						
143	11	4		2	2			4
144	11	2		1				1
145	11	2		1		1		2
146	8	11	2	2	1			5
147	10	5		3				3
148	11	9		3				3
149	9	2						
150	12	7		1	1			2
151	12	6	3	1		1		5
152	9	2		1	1			2
153	9	5	1	2				3

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
154	7	7		1	1			2
155	9	15		1				1
156	9	4			1			1
157	9	2						
158	10	3		1				1
159	10	4		2				2
160	11	1		1				1
161	10	5		1				1
162	9	5		2				2
163	10	3		1				1
164	12	6	1	2				3
165	11	1						
166	5	14	2	3	2			7
167	12	5		2		1		3
168	9	3		2				2
169	11							
170	11	7		1	1			2
171	10	3		1				1
172	12	6						
173	12	4						
174	11	3						
175	11	5		3	1			4
176	11	5		2				2
177	12	3		3		1		4
178	11	3	1	1				2
179	10	1		1				1
180	12	8			1			1
181	12	5	1	1	1	1		4
182	9	6		3	1			4
183	9	2	1					1
184	9	8		2	1			3
185	10	11		4	2			6
186	11	6	1	3	1			5
187	9	7		2	1			3
188	12	3	1					1
189	12	14		3	2			5
190	10	1			1			1
191	10	2		1				1
192	11	2		1				1
193	10	3		2				2
194	11	1			1			1
195	7	1						
196	10	3			1			1
197	10	5	1	1				2
198	9	8		3				3
199	11	9		5	1			6

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
200	8	13	2	3	3			8
201	7	6		1	1			2
202	10	14		4	1	1		6
203	10	1	1					1
204	9	5						
205	9	3		2				2
206	9	7		1		1		2
207	9	2			1			1
208	9	5	1	2		1		4
209	8	2						
210	9							
211	10	4				1		1
212	11	2		1	3	1		5
213	8	7						
214	11	6		2				2
215	9							
216	12	2						
217	12	8		1				1
218	9	2						
219	11	1			1			1
220	11	4	1	2				3
221	10	1						
222	12	4		1	1			2
223	9	7			1			1
224	10	4		2	1			3
225	8	9	2			1		3
226	6	1						
227	10	2				1		1
228	7	2						
229	12	1						
230	11	5		1	1			2
231	12	2		1				1
232	11	3						
233	10	4		1				1
234	12	5			1			1
235	12	8		2		1		3
236	9	2						
237	10	14	1	2	1			4
238	9	8		2				2
239	10	3	1					1
240	10	4	1	1				2
241	10	5	1	3				4
242	12	9		2				2
243	11	1		1		1		2
244	11	2		1				1
245	10	4						

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
246	11	6		1	2			3
247	10	3	1	1				2
248	12	4						
249	11	5		2				2
250	12	2						
251	9	11		5	1			6
252	11	3			1			1
253	10	2				1		1
254	9	6	1					1
255	10	8		3	1			4
256	10	8		2				2
257	10	1			1			1
258	9	7		1				1
259	10	14			1			1
260	11	6	1	2	1			4
261	10	6						
262	7	2						
263	10	5						
264	8	1		1				1
265	11	1		1				1
266	11	2						
267	11	3		1				1
268	8	2						
269	8	2			1			1
270	11	5		1				1
271	11	6		2	1			3
272	9	4			1	1		2
273	10	8		2				2
274	12	2						
275	8	5		1				1
276	9	6		2	1			3
277	9	6		1				1
278	10	10		4	1			5
279	9	6		1		1		2
280	10	2			1			1
281	11	8	4	1				5
282	12	8		2				2
283	12	4		1				1
284	10	4						
285	9	4			1			1
286	10	6		3				3
287	8	5						
288	10	3						
289	9	3			1			1
290	9	1		1				1
291	10	5						

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
292	10	4		2				2
293	6							
294	10	4	2	1				3
295	10	3						
296	11	6	1	2				3
297	9	5		1				1
298	7	5						
299	11	7		1				1
300	11	2		1				1
301	10	2		1				1
302	7	4						
303	11	2			1			1
304	5							
305	9							
306	9	1	1	1		1		3
307	8	2						
308	10	5			2			2
309	11	1						
310	10	4		1		1		2
311	8	5			1			1
312	9	4	2					2
313	10	4		2				2
314	12	6			1			1
315	10	8	1	3	1	1		6
316	9	4						
317	11	3		1				1
318	8	1						
319	10							
320	9	3						
321	8	1						
322	7	1						
323	10	3	1					1
324	10							

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1	13	4						
2	10	1						
3	12							
4	10	3						
5	8	2						
6	10	3						
7	12	3		1				1
8	9							

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
9	11							
10	11							
11	11							
12	10							
13	9							
14	10	3						
15	10							
16	11							
17	11							
18	12							
19	12	7						
20	9		3					3
21	9							
22	10	1		1				1
23	11	3						
24	13	2			2			2
25	8	7		1				1
26	11							
27	8	5			1			1
28	10	5						
29	11	1						
30	7							
31	13							
32	10	5			1			1
33	8	2	1	1				2
34	11	4		1	1			2
35	11	1						
36	11	3		2	1			3
37	10	2						
38	10	6		3				3
39	8	4						
40	10	5		2				2
41	11	3	1					1
42	11	2	1	1				2
43	9							
44	8	7		3				3
45	9	1						
46	11	3						
47	10	4		1				1
48	7	1		1				1
49	8	3	1					1
50	10	3	1	3	1			5
51	10	2	1	1				2
52	10	3		3				3
53	8	7		1				1
54	11	4	2	1				3

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
55	11	4						
56	10	1						
57	12							
58	11	5		1				1
59	10	3						
60	11	3		1				1
61	12	1		1				1
62	10	8		1				1
63	12	8		1				1
64	12	3						
65	12	2						
66	11	3						
67	11	4			1			1
68	9	1						
69	12							
70	9							
71	13	2		1		1		2
72	9	5		1				1
73	11	2						
74	9	1						
75	12	3	1					1
76	9	3			1			1
77	12	2		1				1
78	10	4		1				1
79	11	1						
80	11	4	1	1	1			3
81	10	3			2			2
82	13	1						
83	10	2						
84	12	2						
85	10							
86	11	6		1	1			2
87	10	5	1	1				2
88	11	4		2				2
89	12	6		2	1			3
90	13							
91	10	2		1		1		2
92	12							
93	11	3						
94	11							
95	10							
96	10							
97	10	1						
98	12	2				1		1
99	11	1						
100	11							

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
101	12	4						
102	10	2	1					1
103	10	1		1				1
104	8							
105	9	2			1			1
106	11							
107	12							
108	9	2		1				1
109	9	2						
110	13							
111	10							
112	9							
113	10	2			2			2
114	9	2						
115	7	2						
116	11	1						
117	10							
118	12	1						
119	8			1				1
120	11	1			1			1
121	8							
122	11	2	1		1			2
123	11	2						
124	10							
125	12	3						
126	10	3		3				3
127	9	6	1	1				2
128	11	3						
129	11	2		1				1
130	10	2						
131	11	2						
132	7	4		3				3
133	11	3	1					1
134	14	3		1				1
135	9	2						
136	10	1						
137	8							
138	11							
139	10	4						
140	10	1						
141	9	1						
142	9	3			1			1
143	10	2						
144	15	2						
145	11	2	1					1
146	10							

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
147	11	2						
148	10	2						
149	10	3		1				1
150	12	5		3				3
151	8	3						
152	13	1		1				1
153	12							
154	9							
155	10	2		1				1
156	12	2		1				1
157	10	1						
158	12	1						
159	11	2	1					1
160	10	2	2	1				3
161	11	2		2				2
162	11	3		1				1
163	9	2						
164	13	1						
165	12							
166	10	5		2				2
167	8	2		1				1
168	11	4						
169	12	3						
170	12							
171	12							
172	12	4	1	2				3
173	10	1			1			1
174	12	3						
175	12	3	1					1
176	11	4		1				1
177	11	4		2				2
178	10	3		1				1
179	11	1	1					1
180	11	3		1	1			2
181	11	1	1					1
182	8	2		1				1
183	13	2		2				2
184	10	4						
185	8							
186	11	1		1				1
187	11							
188	12	1						
189	8	2		1				1
190	12							
191	12	2		1				1
192	9	1						

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
193	9							
194	12							
195	12							
196	8	5		1	1	1		3.
197	13							
198	9							
199	13	1						
200	10	5						
201	11	7		4				4
202	9	4		1				1
203	12			1				1
204	9							
205	10	1			1			1
206	11	2						
207	10	3						
208	8							
209	11							
210	10							
211	10	2						
212	11	2		2				2
213	11							
214	11	1						
215	11	1						
216	11	2						
217	9							
218	8	1						
219	13	2						
220	14							
221	13	3						
222	11							
223	13	2						
224	10	2		1		1		2
225	13	3		1				1
226	11	1						
227	10	5	1	3				4
228	12	1		1				1
229	13	1						
230	11	2			1			1
231	10	2						
232	12	6		1				1
233	11	1		1				1
234	11	5	1	1				2
235	12							
236	11	3		1				1
237	12	4						
238	12	3	1	1				2

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
239	10	4	1	1				2
240	12	5	1	1				2
241	11	2	2					2
242	12	2	1					1
243	10	3		1				1
244	10	6	1					1
245	12	1						
246	11	2		1				1
247	10	1		1				1
248	10	3		2				2
249	12	2		2				2
250	12							
251	10	1	1					1
252	12	2						
253	11	2			1			1
254	13	1						
255	12	2		1	1			2
256	11							
257	11	1		1				1
258	8	4	1					1
259	9	2						
260	12	2		2				2
261	11	1						
262	13	2	1	1				2
263	11	2			1			1
264	10	2		1				1
265	8							
266	12							
267	13	4		1	1			2
268	12	2						
269	11	8		1				1
270	11	5		1				1
271	12	3						
272	12							
273	10	2		1	1			2
274	10	3		1				1
275	10	3	1					1
276	10							
277	11	3						
278	11	5	1	1				2
279	10							
280	12	3		1				1
281	9	4			1			2
282	11							
283	12	2			1			1
284	13	2						

Table 13 (Continued).

Plot No.	Plants	C	P	5	4	3	2	Total Borers
285	10	4						
286	11	2						
287	12	6						
288	13	6		2		1		3
289	10							
290	10							
291	12	3						
292	9							
293	13							
294	11							
295	11							
296	12							
297	11							
298	12	3			1			1
299	12							
300	12	2		1				1
301	12	2						
302	13							
303	11							
304	11							
305	11	2		1				1
306	12							
307	12	4		2				2
308	10							
309	11							
310	12							
311	12							
312	11							
313	11	1						
314	12	2			1			1
315	11	1						
316	8	1						
317	11							
318	11							
319	12	2			1			1
320	11							
321	11							
322	12							
323	12							
324	9							